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During the past three years we have made substantial progress toward the goal of a fiber coupled, diode laser pumped 100W cw Nd:YAG minislab laser. We have diode pumped a 1W ring cavity laser and have operated it in a single frequency. We have diode pumped a testbed minislab Nd:YAG laser using fiber coupled diode laser bars and generated 5W of cw, TEMoo mode output power. We have designed and are implementing a 50W cw minislab Nd:YAG laser to be pumped by 25 diode laser bars coupled through optical fibers. We plan, in the second phase of this program, to achieve the 100W cw output power level in a minislab Nd:YAG laser approach proposed as the goal of this research program

In addition, we have demonstrated single frequency control of a high power Nd:YAG laser oscillator by injection locking; have frequency stabilized Nd:YAG oscillators by locking to high finesse Fabry Perot resonators; have absolutely stabilized Nd:YAG to one part in 10^{-13} by locking to iodine; have frequency converted Nd:YAG by second harmonic generation to 11.2W of cw TEMoo mode green output; have demonstrated the first cw 2μm OPO in lithium niobate; and have demonstrated the first cw singly resonant OPO with 2W of output in a single frequency in KTP.

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Final Report
for the period
20 September 1990 to 30 September 1993

Principal Investigator

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High-Power CW Diode-Laser-Array-Pumped Solid-State Lasers and Efficient Nonlinear Optical Frequency Conversion

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and
Efficient Nonlinear Optical Frequency Conversion

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I. Introduction

A. Diode Pumped Nd:YAG Progress

Diode pumped solid state laser technology is advancing rapidly in coherence, efficiency, power and reliability. First demonstrated in 1964 at cryogenic temperatures, recent advances in diode pumped solid state lasers has been reviewed by Byer [1], Fan and Byer[2], and Hughes and Barr [3] and by Kane [4]. The progress in diode pumped solid state laser has been driven by progress in the diode laser pump sources reviewed by Cross *et al.* [5]. It was the introduction of the diode bar operating at 1W of output power at 25% electrical efficiency by Scifres, Burnham and Streifer in 1978 [6] that initiated the modern era of diode pumped solid state lasers. The 1 cm diode laser bar made rapid progress in capability from 1W in 1978, to 12.5W [7] and 38W in 1988 [8], to 76W in 1989, [9] to 120W in 1992 [10]. Microchannel cooling techniques were applied to the devices in 1990 [11] and two dimension stacked arrays and integrated arrays have become the focus of recent developments.

The diode laser capability made the transition from the research laboratory to commercial products in 1984. Since that time, the capabilities and performance of the diode laser sources have improved. The initial cost of the diode laser sources were measured in thousands of dollars per milliwatt in 1984. A decade later products are priced at $300 per watt of average output power. The price of the devices, depending on market growth, is expected to fall by 30% per year and reach less than one dollar per watt by the end of this decade. For the first time since the invention of the laser, solid state technology is driving the cost and performance of the laser sources in a manner that is very familiar to the solid state electronics markets.

Every advance in solid state laser technology has been preceded by an advance in the pumping source technology. However, how best to engineer a solid state laser to take advantage of the new pump source is a combination of science and the art of engineering. Our interest at the outset of this program was to take a laser design approach that accomplished the following: scalability to high average power levels; single frequency, single transverse mode, cw laser operation; simple laser head design that could be easily repaired while operational; separation the thermal engineering problems of the diode laser pump sources and the laser head; and ability to upgrade the diode lasers without forcing the redesign of the complete laser.

These design goals were best met by using diode lasers coupled to optical fibers as the pump source and by using the side pumped slab geometry for the laser head. Figure 1 shows an early schematic of this fiber coupled, diode laser pumped, minislab laser design. Our early enthusiasm for this approach met with considerable opposition from others in the laser engineering community. However, recent progress in our laboratory, and progress by others who are exploring this design, coupled with the advances in the diode pump sources, have demonstrated the benefits of the fiber coupled, side pumped, slab geometry.

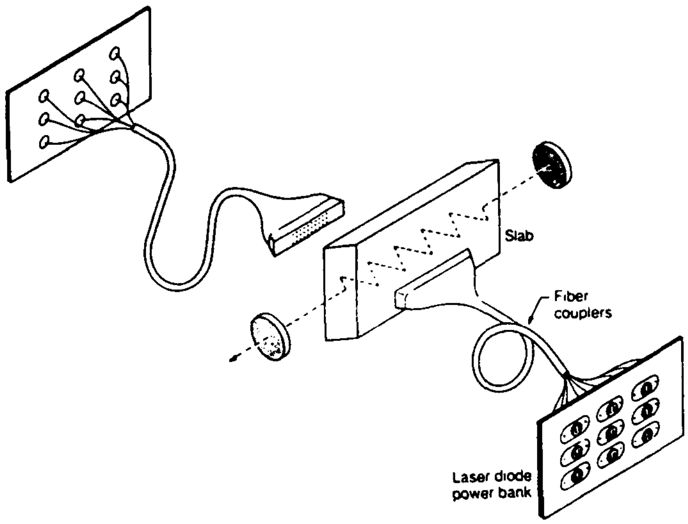

Figure 1. Schematic of the proposed high average power solid state laser pumped by diode lasers coupled via optical fibers. This design offers that advantages of power scaling, separation of the thermal problems of the diode cooling and the slab cooling, possibility of repair during operation, and the opportunity to upgrade diode lasers without forcing a redesign of the slab laser head.

Other laser design approaches were considered before adopting the preferred design approach sketched in Figure 1. It is useful to describe these other approaches with comments on their limitations and demonstrated performance to date.

The first option facing the laser engineer is pulsed pumping vs cw pumping. Our long term motivation for the application of the high average power solid state laser is to coherent laser radar, coherent laser interferometry and coherent remote sensing including global wind sensing. With these applications in mind, and acknowledging that the diode laser is basically a continuous wave device, we elected to pursue the design of a highly coherent, diffraction limited, cw laser.

The second option facing the laser engineer is end pumping vs side pumping. It is clear from early work and more recent work by Kaneda *et al.* [12], and by Tidwell *et al.* [13] that end pumping has average power limitations due to thermal focusing, thermally induced birefringence, and finally thermally induced fracture of the solid state laser media. A debate has raged within the solid state laser community about the maximum average power level that can be achieved by end pumping. The consensus at this time is that 100W is a maximum set by fracture of the laser medium but that 20W is the maximum set by thermal focusing and birefringence. Because of these limitations, we elected to avoid end pumping and to pursue a design that involved side pumping.

The third option facing the laser engineer is the geometry of the side pumped gain media. The options are to side pump a cylindrically shaped gain media, a rod, or to side pump a rectilinearly shaped gain media, a slab. The theory of slab geometry lasers has been developed early by groups at General Electric Corporation led by the inventor of the slab laser, Joe Chernoch,[14] and by the group at Stanford University [15]. The theory shows that the average power of a side pumped rod laser scales as the length of the rod, independent of the rod diameter. The side pumped rod suffers from thermal focusing, thermal induced birefringence, and nonuniform gain and saturation which leads to nonuniform energy extraction.

The side pumped slab laser offers power scaling as the product of the length of the slab and the width of the slab. The zigzag slab geometry offers correction for the thermal induced cylindrical lens caused by optical pumping and cooling through the face of the slab. The zigzag optical path allows for efficient energy extraction of the optical power with a uniform beam cross section. The average power of a slab geometry laser scales as

the thermally cooled area of the slab and with pump power up to the thermal stress limit of the slab gain medium. Previous research has shown that this scaling can be extended to hundreds of kilowatts of average power for Nd:YAG slab lasers of modest ten centimeter size. Further, by moving or rotation the slab laser medium to increase the thermal cooling area, the average power can be scaled to megawatts. For these reasons we elected to pursue the side pumped slab geometry laser design.

The diode pumped slab laser design that we elected to pursue has some disadvantages. In particular, for cw operation the optimum slab dimensions are millimeters in thickness to allow for high extraction efficiency of a TEM_{00} spatial mode. This, in turn, forces the diode lasers to pump a small volume of slab of approximately 1.5mm x 1.5mm x 25mm. For these small dimensions, the optical absorption is less than unity so that there is some loss of overall laser efficiency.

The way past this dilemma is to pump larger slab dimensions at higher pump power levels to maintain the gain of the solid state laser for efficient operation. However, larger gain media force operation in other than a TEM_{00} mode. The solution is to operate the laser in an unstable resonator mode to efficiently extract the power. However, the unstable resonator requires adequate laser gain to overcome the high output coupling. This in turn requires higher pump power levels to reach the desired e^3 gain levels. If cost were not an issue, the laser engineer would elect to design and construct the cw laser at power levels in excess of 100W. However, the cost to purchase the required pump diode laser arrays is a critical issue that dictates a more prudent approach to the research and development effort.

We understood early in this program that the minimum cw power level that allows unstable resonator operation is at or above 100W which requires 500W of diode pump power. In March of 1990, the commercial price of the diode laser bars was such that 5W of power from a fiber coupled diode laser cost $14,000. The cost for 500W of diode power was a prohibitive $1.4 million dollars. Therefore, we elected to work with the diode laser manufacturers to assist with the development of fiber coupled diode laser arrays and to reduce the cost. We initially purchased 10 diode lasers at $14,000 each, tested these devices, and worked with the manufacturer to improve their performance and reliability. Two years later, we purchased 25 diode laser bars coupled to optical fibers that provided 10W of output power from the fiber at a cost of $7500. At this cost the diodes for a 100W laser is a more reasonable $375,000.

Today, in the second phase of this program, we continue to work with the diode laser manufacturers to obtain higher output power, higher fiber brightness and coupling efficiency at lower cost. We expect that the cost of 10W of fiber coupled diode power will be $3000 by mid-1994. At this price the cost of the diodes for the 100W cw laser will be $150,000. This cost is reasonable for a research project with the goal of demonstrating a state-of-the-art diffraction limited, diode laser pumped, Nd:YAG laser. The second phase of this research program will proceed toward the goal of demonstrating the 100W output power at a cost for the laser diodes as projected above.

The demonstration of a diode pumped, cw, Nd:YAG minislab laser is one step toward establishing widespread commercial and military application of higher power diode-pumped lasers. To make this transition, this type of laser source must compete on price against lamp pumped cw Nd:YAG lasers. Today, it is less expensive to manufacture and sell diode pumped Nd:YAG lasers at the 1W to 5W average power level than the corresponding lamp pumped lasers. The cost of diode lasers is decreasing at a rate such that the cross-over cost of diode-pumped lasers vs lamp-pumped lasers allows the diode pumped Nd:YAG average power level to increase a factor of 10 every two years at a fixed price. Therefore, we can expect to see commercial products at the 30 to 50W average power level in 1996 and at the 300 to 500W average power level in 1998. Our research effort at Stanford University is informing the laser community about the design choices for these future products. Our research program has trained, and is training today, the scientists and engineers that will bring these products to reality.

Simultaneously with the laser development program, we have explored nonlinear frequency conversion of these cw lasers. Our early work showed that by controlling losses we could frequency doubled a 50mW cw Nd:YAG laser and generate 30mW of 532nm at 56% conversion efficiency. During this program we have extended those early results to 6.5W of 532nm and recently to 11.2W of cw, single axial mode output at 532nm at 60% conversion efficiency. Further, we have demonstrated the first cw optical parametric oscillator (OPO) at 2μm in total internal reflection geometry lithium niobate OPO. Finally, undertaking a difficult task, we have demonstrated the first cw singly resonant optical parametric oscillator (SRO) in KTP pumped by 532nm. This cw SRO operated at 78% slope efficiency and generated 2W of cw output for 7W of pump power. The SRO operated in a single axial mode with excellent frequency stability.

B. Program goals and accomplishments

The progress in laser-diode pump sources offers an opportunity for significant advances in solid state lasers and nonlinear frequency conversion. It was in this environment that this research program on cw high average power laser-diode-pumped solid state lasers was initiated in September 1990.

The program goals were ambitious. The original program goals were to:

•frequency stabilize Nd:YAG laser oscillators by locking to external cavities;
•investigate injection locking for single axial mode control;
•characterize the fiber coupled diode laser pumped 8W cw minislab Nd:YAG laser oscillator pumped by 56 Sony 1W diode lasers;
*design and construct a 100W, cw, diffraction limited, Nd:YAG minislab laser;

•efficiently double a cw Nd:YAG laser;
*generate ultraviolet radiation at 266nm;
*investigate 2.1μm coherent sources with up to 15W of average output power;
•investigate the operation of a cw singly resonant optical parametric oscillator

The goals denoted by '•' were accomplished and completed during the first phase of this program and are described in section II. The goals denoted by '*' are under investigation and are part of the program goals in phase II of this research program.

In brief, we have successfully frequency stabilized Nd:YAG to external high finesse optical cavities. The work has led to short term frequency stabilities of better than 1Hz or a stability of one part in 10^{14}. We have stabilized frequency doubled Nd:YAG to molecular iodine at 532nm. Stabilization using Doppler free techniques reached an absolute frequency stability of better than 60Hz or one part in 10^{13}. This frequency stabilized laser will find applications in precision metrology including the control of sub-micron lithography stations.

We have explored injection locking for the frequency and spectral control of high average power laser oscillators. For example, we have used a 40mW single frequency ring Nd:YAG laser to control the spectral characteristics of an 18W Nd:YAG lamp pumped

laser. Recently, we have measured in detail the spectral properties of an injection locked diode pumped minislab Nd:YAG laser. We have patented the concept of injection locking of solid state lasers; a concept that is now finding its way into commercial products.

We have designed, constructed and operated for one year a fiber coupled, laser diode pumped, minislab Nd:YAG laser. This laser is pumped by 56 1W diode lasers. It generates 8W of cw output in a TEM_{00} mode for 30W of absorbed power when operated in a standing wave cavity. It operates in a ring cavity configuration at 5.5W of output power under injection locked, single axial mode conditions. The laser is stable, has frequency and amplitude noise properties that are now well characterized. Further, it has proven to be very reliable with no diode laser failures after a one year period. Finally, individual diode lasers used for pumping can be turned off at random and replaced by reserve diodes at no loss in output power or single frequency operation. With this feature fiber coupled diode laser pumped Nd:YAG laser can be repaired while operational.

The design and demonstration of progress toward the goal of the 100W cw Nd:YAG minislab laser has taken place in discrete steps. The first step was to design and demonstrate a 1W cw ring laser that operates in a single axial mode by injection locking. The second step was to design and test a side pumped minislab Nd:YAG laser pumped by six fiber-coupled laser diode arrays. This minislab laser operates at 5W of cw output power in a TEM_{00} mode for 14W of pump power. With this laser we have tested engineering design principles that will be used in a 50W cw minislab laser to be completed in January, 1994. The 50W laser is pumped by 25 fiber coupled laser diode arrays. It is expected to operate at greater than 65W of output power in a multi-spatial mode and at 50W of output power in a TEM_{00} mode. The minislab dimensions for the 50W laser are 2mm x 2mm x 40mm. Experience gained in the operation of the 50W laser will form the basis for the design of the 100W laser that is planned for operation in late 1994 in the second phase of this program.

Early in the research program we began investigation of nonlinear frequency conversion of the Nd:YAG laser. Based on prior results of external cavity resonant second harmonic generation, we used lithium triborate (LiB_3O_5 or LBO) to frequency double an injection-locked, lamp-pumped 18W cw Nd:YAG laser. In this experiment, we generated 6.5W of 532nm output for 18W of laser input power. The generated 532nm radiation was used for frequency extension into the ultraviolet by external cavity resonant harmonic generation in BBO. Preliminary results led to 30mW of cw ultraviolet output.

In an extension of the second harmonic generation work, we frequency doubled a 24W cw Nd:YAG laser in LBO to generate 11.2W of 532nm output at 60% conversion efficiency for the radiation that was coupled into the resonant SHG cavity. This is the highest single-frequency cw output power obtained by SHG reported to date. The 532nm output was used to pump a cw singly resonant optical parametric oscillator. The 532nm source has operated since late June, 1993 and has proven to be a reliable.

We have demonstrated the first cw OPO pumped by 1064nm radiation. This OPO is based on total internal reflection (TIR) geometry in lithium niobate and operated with a threshold of 130mW with output near degeneracy at 2.1μm. The low loss of lithium niobate bodes well for extension of this OPO to high average power operation in the future.

Finally, we have demonstrated the first operation of a cw singly resonant optical parametric oscillator (SRO). The device utilized KTP as the nonlinear crystal and was pumped by the cw, single mode, 11.2W 532nm doubled Nd:YAG laser. A combination of available pumped power and low loss nonlinear crystal of KTP led to successful operation of this cw SRO. When pumped two times above threshold the SRO converted 7W of input green to 2W of single frequency output with a slope efficiency of greater than 78%. The SRO operated in a single axial mode. This demonstration experiment sets the stage for high average power OPO's in the future.

In the next section we describe in detail the research results generated during the three years of this program. We first focus of progress in diode pumped Nd:YAG laser technology and then consider progress and demonstrated results in nonlinear optical frequency conversion.

II. Research Results

A. Diode Pumped Mini-Slab Nd:YAG

Frequency Stabilization and Injection Locking

The diode-laser pumped monolithic NonPlanar-Ring Oscillator (NPRO) has proven to be the most stable solid state laser. Invented in 1984 by Kane and Byer [16] to meet the needs of coherent laser radar [17], the NRPO has evolved to become the 'quartz crystal' of the optical frequency range. The NPRO power level has increased from 3mW in 1984 to 300mW by 1990 while the linewidth has decreased from 20kHz in 1986 to less than 1Hz by 1992 [18, 19, 20, 21]. In recent experiments, N. Sampas *et al.* [22] studied the long term stability of the NRPO locked to independently stabilized Fabry-Perot interferometers. They showed that the daily variations in the beat note between two independent laser systems could be less than 1MHz. For times on the order of one second, the two independently stabilized lasers showed an Allan variance beat note of 1 Hz or $1{:}10^{-14}$. With improvements in the thermal isolation of the reference interferometers, it is expected that the relative linewidth of these solid state laser oscillators will be reduced to less than 10mHz.

Absolute frequency stabilization of the frequency doubled NPRO has been studied by A. Arie *et al.* [23]. Arie frequency doubled two 300mW NPRO oscillators in monolithic lithium niobate crystal doublers to generate up to 100mW of cw 532nm output. The green was then modulated and passed through a temperature controlled cell containing iodine vapor. The Doppler free spectra of iodine provided a rich spectrum to which the NPRO laser could be locked by FM locking techniques. Two independent laser oscillators were stabilized and compared by the two-time Allan Variance technique. The laser oscillators reached a level of stability of 70Hz when time integrated over 30 seconds.

This result has practical applications in measurement systems since the 1064nm and the 532nm are exact harmonics and therefore can be used to remove length fluctuations due to atmospheric variations for precision metrology. Further, absolutely frequency stabilized Nd:YAG may prove to be the 'optical clock' of choice for frequency measurements in the visible and the near infrared.

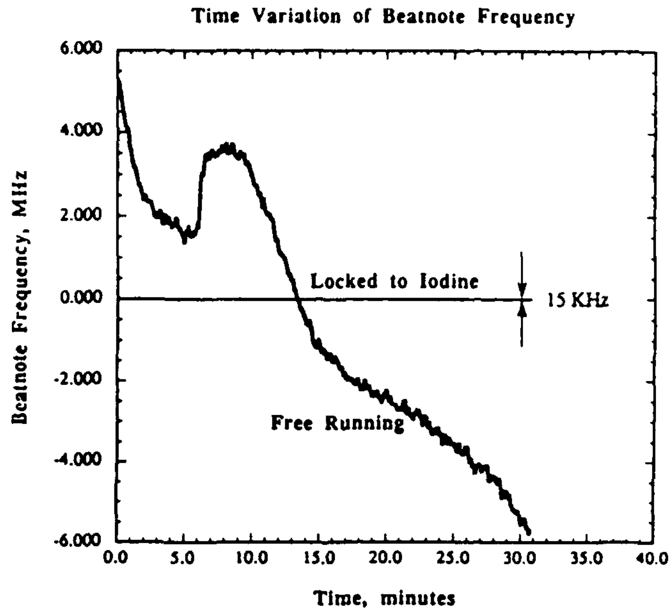

Figure 2. Time variation of the beatnote frequency measured at 1064nm for iodine stabilized Nd:YAG laser oscillators.[after Arie *et al.* ref 23] Frequency stable NPRO's are the key element in obtaining high power single frequency Nd:YAG via injection locking.

The intrinsic frequency stability of the monolithic NPRO allows the injection locking technique, originally introduced at microwave frequencies by Adler [24] to be extended into the optical frequency range. Injection locking allows the spectrum of a high power slave oscillator to be controlled by a low power, but frequency stable, master oscillator.

Injection locking was first demonstrated in Nd:YAG by Nabors *et al.* [25]. Nabors used a 40mW NPRO to injection lock a 13W cw lamp-pumped Nd:YAG laser oscillator. Measurements of the spectrum showed that the high power oscillator operated at the 13kHz linewidth of the low power NPRO master oscillator. Recently injection locking has been extended by Stephen Yang such that a 300mW NPRO master oscillator controlled the spectrum of a 24W cw lamp-pumped Nd:YAG laser oscillator. The single frequency oscillator was then frequency doubled by external cavity resonant SHG in LBO to generate 11.2W of single mode 532nm output.

In an extension of injection locking, Day *et al.* [26] and E. A. P. Cheng *et al.* [27] have phaselocked Nd:YAG NPRO laser oscillators. Cheng *et al.* [27] showed that Nd:YAG laser oscillators could be phaselocked or coherently added in series. This injection chaining offers the potential for high power at improved reliability for applications that demand extreme operational lifetimes without failure.

Fiber coupled 8W cw minislab Nd:YAG laser

One of the tasks at the beginning of this research program was to study the characteristics of a fiber-coupled, laser-diode pumped, miniature Nd:YAG slab laser. This laser was designed to meet the needs of the Laser Interferometry Gravitational Wave Observatory (LIGO) research program and was supported jointly by the National Science Foundation and by the Army Research Office under this program. Alex Farinas designed the minislab laser that utilized 56 Sony 1W diode lasers coupled to optical fibers [28]. The fibers were bundled into a single line approximately 25mm in length and placed in close proximity to the Nd:YAG slab of dimensions 2.5mm x 1.5mm x 24mm. A schematic of the Nd:YAG laser head is shown in Figure 3. The laser slab is conduction cooled through a thin indium foil to a copper heat sink. What is unusual about this slab geometry is that the cooling is on the face orthogonal to the pumping and to the zigzag optical path. The performance of this "orthogonal slab" was first investigated theoretically by T. Kane *et al.* [29]. The advantages of this geometry are the ease of cooling and the low optical loss of the zigzag path Nd:YAG face which sees only an air interface. A disadvantage of this geometry is the strong cylindrical thermal focusing due to face cooling perpendicular to the zigzag optical path. The cylindrical lens limits the average power of this configuration to approximately 10W. This laser is known as the Stanford Ten Watt Laser Design. A Schematic of the injection locked laser optical layout is shown in Figure 4.

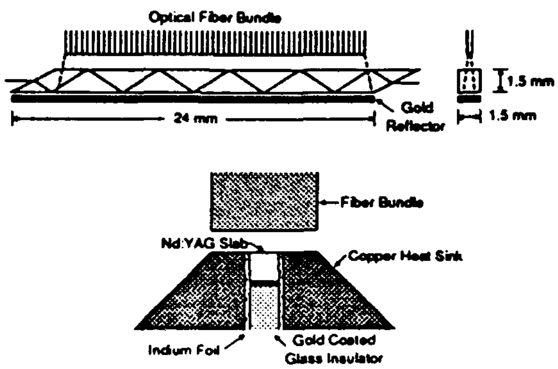

Figure 3. Schematic of the conduction-cooled, fiber-coupled, laser-diode-pumped, cw Nd:YAG minislab laser head. Pumping is orthogonal to the conduction cooled faces. The laser is pumped by 56, 1Watt laser diodes coupled to 300μm core diameter fibers. A gold coated mirror reflects the pump radiation back through the 1.5mm thick Nd:YAG slab for efficient pumping.

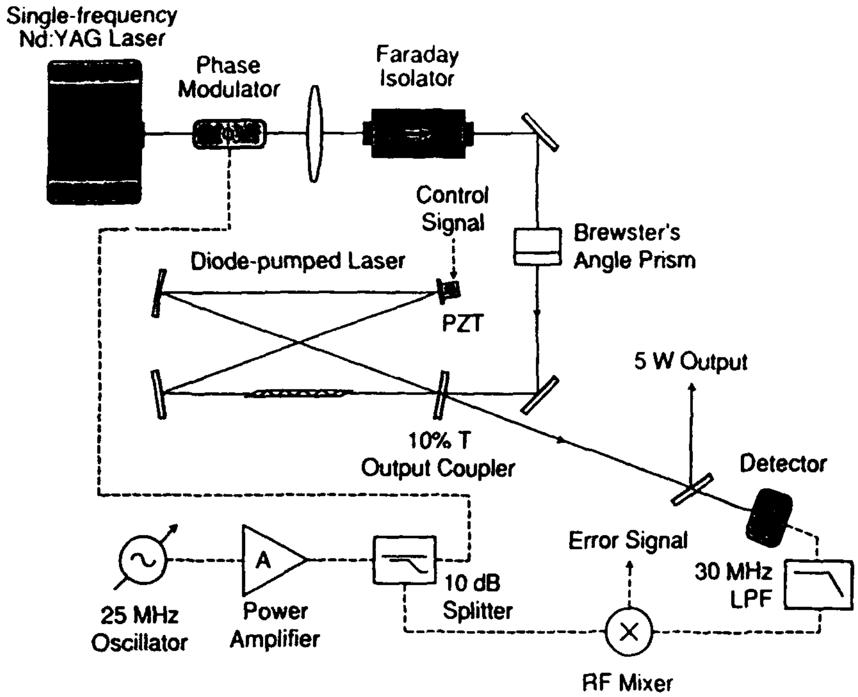

Figure 4. Schematic of the injection locked, diode laser pumped minislab Nd:YAG laser cavity configuration. A 300mW NPRO is the master oscillator. The Stanford 10 Watt laser has generated 5.5W of cw output power when injection locked. The injection locked output has been frequency doubled using external cavity resonant second harmonic generation in LBO to generate 1W of 532nm output.

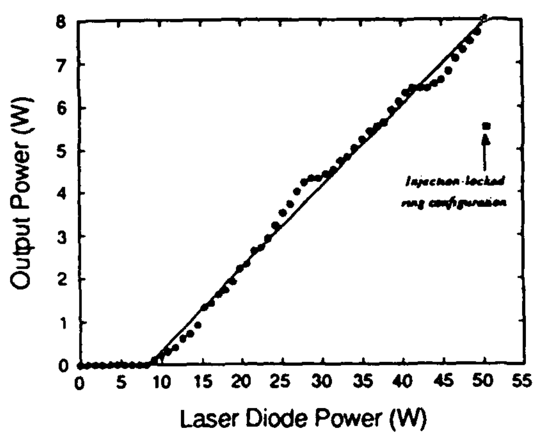

Figure 5. Input-output power curve for the standing wave laser vs input diode laser power. Each dot represents the addition of a single diode laser. The threshold pump power is 8.3W. The maximum output power is 8.0W in a TEM_{00} mode. The slope efficiency is 19%. The single point is the 5.5W output power for a ring cavity oscillator that is injection locked.

The fiber coupled laser has operated since December 1992 in normal laboratory environments. During that time not one diode laser has failed. Further, the laser head has proved to be robust. One advantage of the fiber coupled diode laser pumping approach is the ability to build in redundancy in the pumping source so that the laser can be repaired during operation. This was tested experimentally by turning off one diode laser and treating it as a reserve laser diode. A second, random laser diode was then also shut off reducing the Nd:YAG power level from 5.4W to 5.3W. The reserve diode laser was then turned on which returned the Nd:YAG laser to its original operating power level of 5.4W. During this cycle the Nd:YAG laser remained injection locked. This experimental demonstration is illustrated in Figure 6.

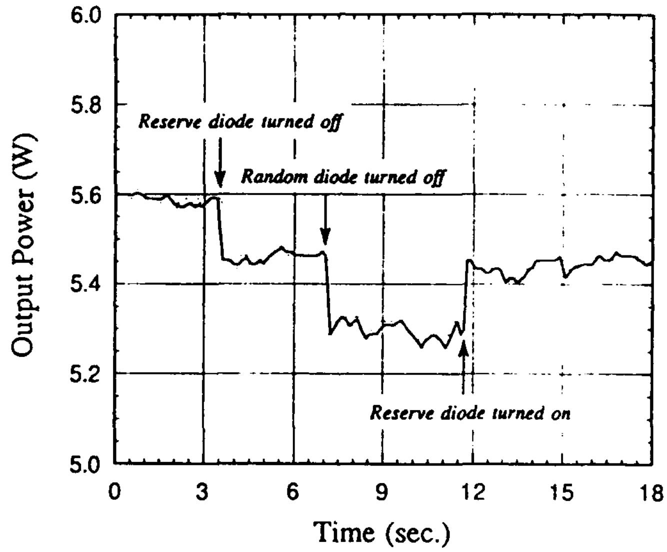

Figure 6. The output power of the injection locked ring Nd:YAG laser as a function of time. A reserve diode laser is turned off, a second randomly selected diode laser is then turned off simulating a failed diode. The reserve diode laser is turned on returning the Nd:YAG laser to it operational point. During this cycle the Nd:YAG laser remained injection locked. This cycle shows that fiber coupled diode lasers have a soft failure mode and that they can be repaired during operation without loosing single frequency operation.

TABLE I. SUMMARY OF LASER AMPLITUDE AND FREQUENCY NOISE

Source	Relative intensity noise ($1/\sqrt{H}$)		Frequency noise ($Hz/\sqrt{Hz}$)	
	@ 100 Hz	@ 1 kHz	@ 100 Hz	@1 k Hz
300-mW master oscillator	1.8×10^{-7}	1.8×10^{-7}	100	20
5.5-W, injection-locked power oscillator	1.7×10^{-6}	1.7×10^{-6}	100	20
Typical Argon-ion laser	2.0×10^{-5}	6.0×10^{-6}	3×10^{4}	10^{3}

An important feature of this laser diode pumped solid state laser is the relative intensity noise. It was expected that diode pumping coupled with conduction cooling would reduce the acoustic noise in the laser resonator. The laser amplitude and frequency noise were measured and are shown in Table I. It is noteworthy that the noise characteristics of this injection locked Nd:YAG laser are more than one order of magnitude improved relative to an argon ion laser. The improved relative intensity noise and spectral density of frequency noise are important aspects of this laser for applications such as coherent laser radar.

We have characterized a first generation, fiber-coupled, laser-diode pumped, miniature slab Nd:YAG laser. This laser is the prototype for the lasers that will lead to a 100W cw minislab Nd:YAG laser. The fiber coupled laser operated at good efficiency; operated with conduction cooling at low optical loss; operated in a single axial mode when injection locked; and operated with noise characteristics an order of magnitude improved relative to an argon ion laser. This miniature Nd:YAG slab laser illustrates the advantages of fiber coupled pumping; of remotely locating the diode pump lasers with their associated cooling problems from the laser head; the advantage of a soft-failure mode if a pump laser diode fails; and the advantage of repair during operation which is critical to a number of potential applications. Finally, this fiber-coupled, laser-diode pumped Nd:YAG laser has operated for a one year period without a laser diode failure. As operational time is gained in the future, this laser will offer statistically significant information about the life of the laser diode pump sources.

Progress toward a 100W cw, miniature slab Nd:YAG laser

This section describes the progress toward the realization of a 100 Watt, cw, diffraction limited Nd:YAG laser. The potential for a laser-diode pumped, slab-geometry laser was first demonstrated by Reed *et al.* in 1988 [30]. In that first experiment, a pulsed laser diode array pumped miniature slabs of Nd:YAG and of Nd:Glass. The experiment showed that the laser diode could be efficiently coupled into the miniature slab and that the pumping efficiency was as expected. Based on that early result, we undertook preliminary design studies for a cw laser diode pumped slab Nd:YAG with power output at the 100W level. This study formed the basis for the proposal submitted in March 1990.

Modeling

The early studies of the 100W cw minislab Nd:YAG laser focused on the laser aspects of the device. That is, we assumed a slab geometry, calculated the dimensions of the slab for the zigzag optical path, assumed a gain cross section for Nd:YAG, an absorption cross section at the pump wavelength of the laser diodes, and assumed a fixed loss in the Nd:YAG laser medium. Given these parameters, we estimated that the 100W Nd:YAG laser would operate at a 30% slope efficiency, have a 90W pump threshold power, and generate up to 120W of output power for 500W of input laser-diode pump power. The calculated output power and the laser parameters are shown in Figure 7 and Table 2.

Although the details of the laser design have changed during the past three years, the expected performance has remained the same. However, to realize the predicted

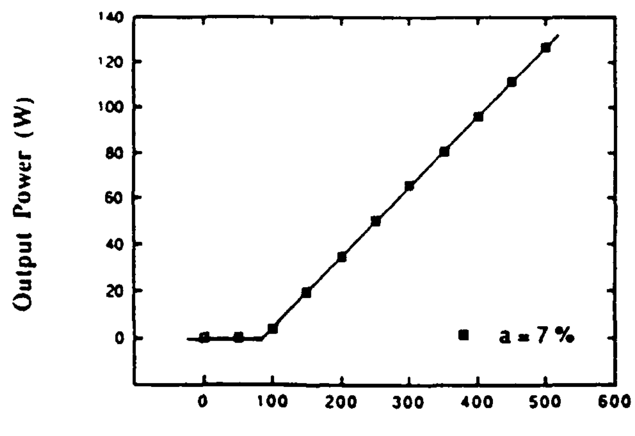

Figure 7. The calculated output power vs input laser-diode pump power for a cw, mini-slab Nd:YAG laser. The round trip losses in the laser resonator are assumed to be 7%. The slab dimensions for this calculation are 1.5mm thick, 6.0mm wide and 26.3mm long.

TABLE II. 100-WATT DIODE-LASER-ARRAY-PUMPED ZIGZAG SLAB LASER OPERATING PARAMETERS

$g =$	1.60
$a =$	7%
$P_{out} =$	120 W
$\eta_{sl} =$	30.3%
$P_{th} =$	90 W

performance level with diffraction limited output in a single axial mode has taken a great deal of modeling effort complemented by experimental measurements of laser systems. In this way, we have progressed from an 'idea' toward a realizable laser system.

The computer modeling consists of three packages: computer modeling of the laser performance as illustrated by Figure 7; computer modeling of the thermal and stress properties of the slab; and computer modeling of the laser resonator. A description of the capabilities of these modeling tools is presented in a paper by Shine *et al.* titled "Design considerations for a 50-watt cw, fundamental mode, diode-pumped solid-state laser," [31]. The model was applied to a Nd:YAG slab of the dimensions shown is Figure 8. We assume a Brewster angle slab of thickness 1.5mm, width 6.0mm and length 26.3mm. A Brewster angle slab was selected because it minimizes loss and maximizes the spatial mode overlap and power extraction within the slab.

The second of the three packages models thermal loading and induced stress of the slab. This package consists of three programs. The first program computes the thermal loading of the slab under pumping conditions. It allows the pumping distribution to be varied to minimize the thermally induced stress. An example of this capability is illustrated in Figure 9. The pumping power delivered to the slab is through an array of 25 individual fibers. With discrete pumping, a question arises how best to arrange the fibers to derive a uniform gain profile for the laser beam and to minimize the thermal induced stress in the slab. By using the program in an interactive way, a fiber arrangement shown in Figure 9 was derived. This arrangement is referred to as the "orange-grove" configuration of fibers. It closely resembles a uniformly pumped slab with a discrete set of fibers delivering the pump power from the laser-diodes.

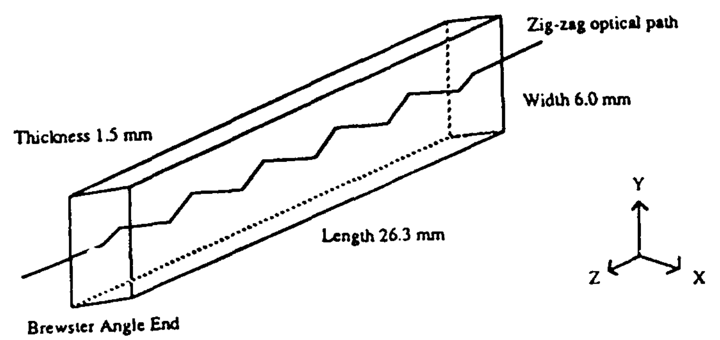

Figure 8. Diagram of the typical slab geometry with dimensions shown for the modeling studies.

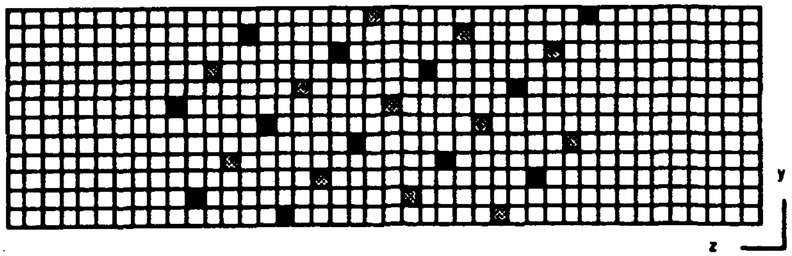

Figure 9. A diagram of the "orange-grove" pumping arrangement for the fiber coupled laser-diodes. The solid boxes are on one side of the slab; that shaded boxes on the other. This fiber arrangement produces uniform gain in the slab and minimizes the thermal stress. The boxes represent the size of the grid used in the finite element analysis code that calculates the temperature distribution and stresses in the slab.

The second component of the thermal loading and induced stress package is a finite element analysis program, which runs on a DEC workstation, and generates an image of the pumped slab with the distortion of the slab amplified for easy visualization. Figure 10 shows an image of the slab under pumped conditions. The output of the computer model is in full color to aid in the visualization of the high and low regions of the thermally distorted slab. Here we have reproduced the output in black and white.

The thermally distorted slab is the starting point for the third program of this set. The third program propagates a wavefront through the slab and models the optical resonator. The wavefront distortion caused by the thermal load is determined in the propagation calculation. An example of the calculation is that of the residual cylindrical distortion caused by the slab in the non zigzag path dimension. For this optical path through the slab, the distortion is not compensated by the zigzag optical path. Figure 11 shows the calculated cylindrical distortion which, in this case, is a cylindrical lens of 184cm focal length. If a correction lens is used within the optical resonator, this cylindrical distortion of the slab can be compensated. The compensated optical path distortion is less than 1/4 wave over the full 6mm width of the slab. This calculation gives promise that a properly designed slab with a properly designed resonator can produce an output waveform that is diffraction limited. This is important since phase-front compensation methods, such as wavefront conjugation using stimulated Brillouin scatting, are not possible for cw lasers.

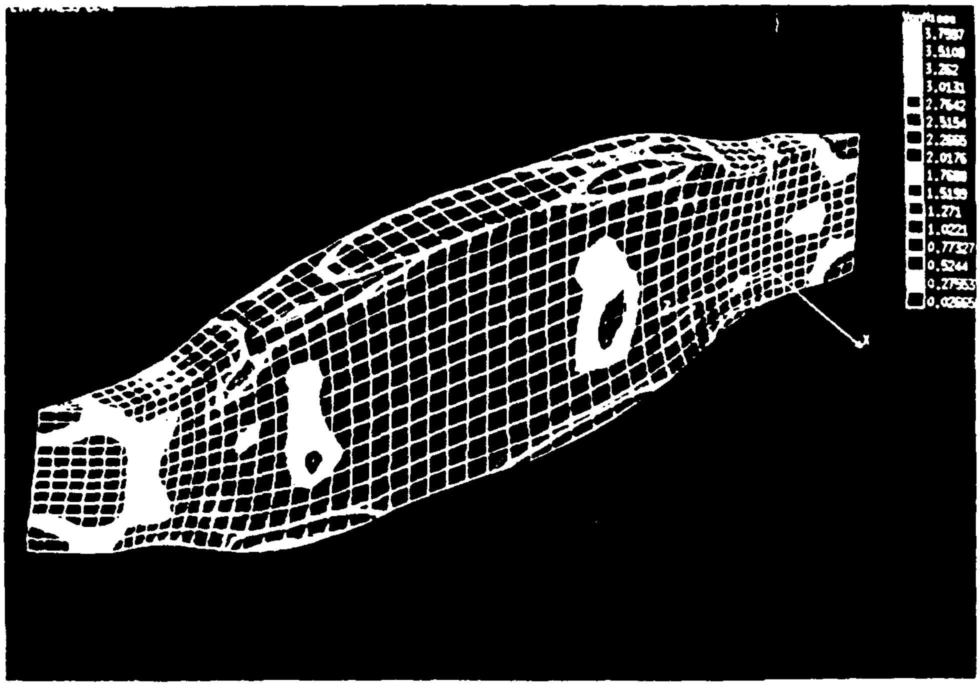

Figure 10. A computer image of the thermally distorted slab under pumped conditions. The zigzag optical path compensates for the thermal lens in the pumped and cooled direction. A residual cylindrical lens remains in the width of the slab or the y direction.

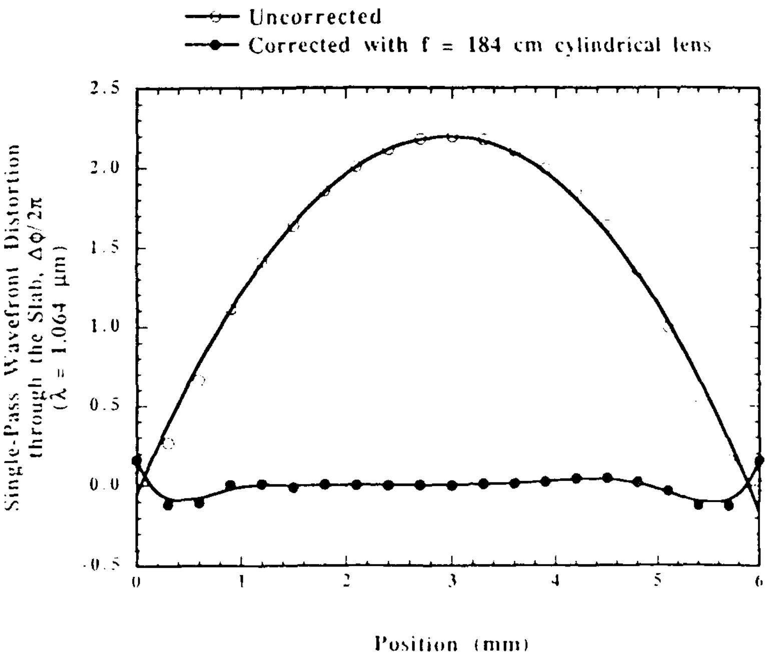

Figure 11. A calculated thermally induced cylindrical lens in the pumped slab. The wavefront distortion can be corrected to better than 1/4 wave by the use of an f = 184cm lens.

An example of the resonator analysis capability of this program is illustrated by the design of a stable-unstable resonator to optimize the extraction of the optical power. As mentioned above, the TEM_{00} mode resonator efficiently extracts the optical power for miniature slab dimensions. Typically, the diameter of a rod or the width of a slab is chosen to be three times the mode spot size for the TEM_{00} mode. Because the stability of the resonator to misalignment degrades rapidly for long radii mirrors, the spot size of TEM_{00} mode resonators for 1064nm radiation is rarely in excess of 0.800mm. The maximum diameter of a rod laser, or the width of a slab laser for efficient TEM_{00} mode operation is then 2.4mm. For a 100W laser we have elected to design with a slab that has a width of 6mm. For this slab, we need to extend the transverse mode by use of an unstable resonator in the one dimension. Thus we have modeled a stable-unstable resonator for efficient power extraction from the slab.

Figure 12 shows the diagram of the Stable-Unstable resonator. The resonator is configured into a ring for injection locked single frequency operation. The resonator incorporates cylindrical elements to compensate for the slab distortion illustrated in the previous figure. Further, the slab uses a Super-Gaussian mirror as the output coupler. The cavity is stable in the slab thickness direction and unstable in the slab width direction. The super-gaussian allows the output mode of the resonator to be designed for a flat top power distribution. Details of the design of this resonator can be found in Shine *et al.* [31].

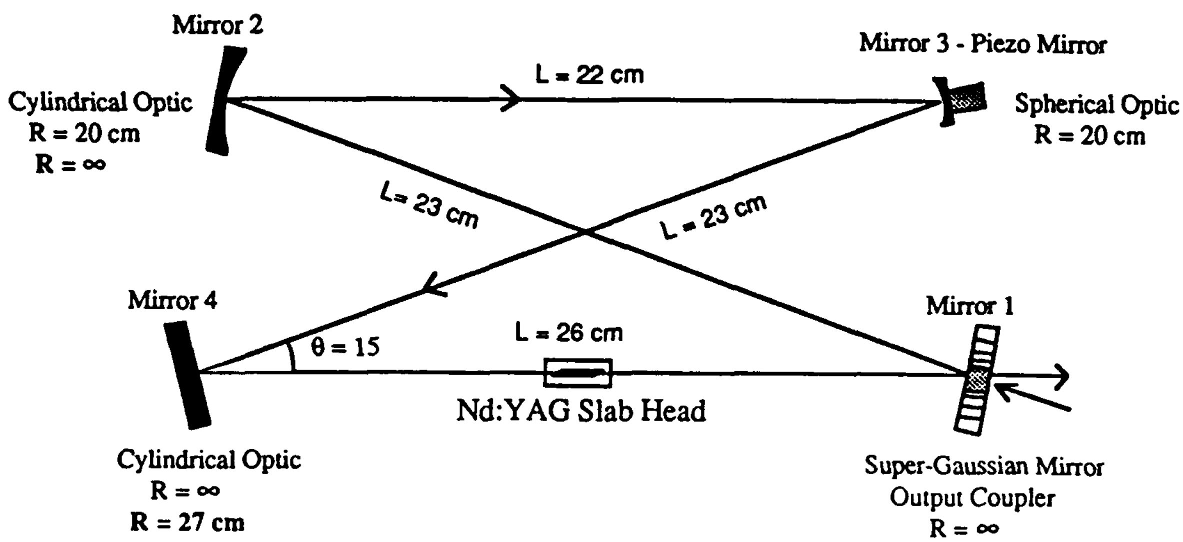

Figure 12. Schematic of the stable-unstable resonator design to optimize the extraction efficiency of the minislab Nd:YAG laser. The tangential direction is stable while the sagittal direction is unstable thus filling the 6mm width of the slab. The bold optics are saggital cavity elements.

For a super-gaussian mirror resonator, the output beam intensity profile depends upon the magnification and the order of the super gaussian reflector. The output beam profile can be designed to be flat topped, which is ideal for nonlinear frequency conversion processes. A maximally flat beam is obtained when the reflectance R_0 and the magnification with super-gaussian order n, M^n have a product equal to unity. For R_0M^n greater than unity the mode has a dip in the center. For R_0M^n less than unity the mode has a gaussian shape. Figure 13 illustrates the expected output profiles from that stable unstable resonator for choices of the R_0M^n values. For the laser modeled in this study, we have selected a magnification of M = 1.5 and a low order super gaussian of n = 3 which results in a flat topped output beam of R_0 = 0.3. This results in an output coupling transmission of T = 77%. For a fixed gain of 2, the output power of the laser is nearly constant for a transmission range that lies between T = 0.2 and T = 0.7. Thus this resonator should provide an efficient approach to the power extraction from a cw slab laser.

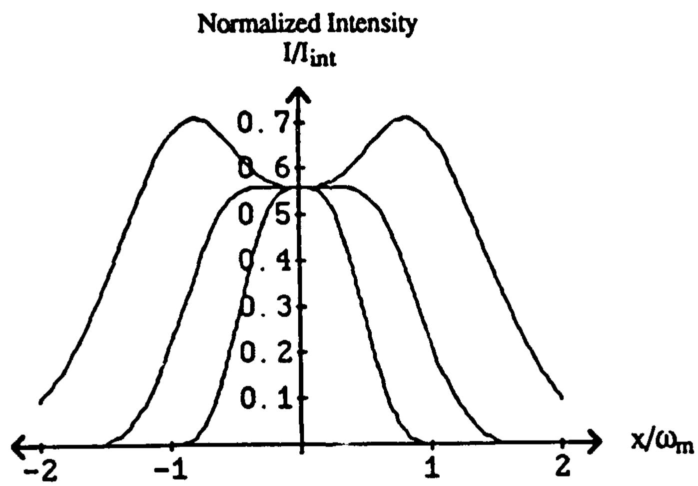

Figure 13. Plots of the calculated output beam profile for a stable unstable resonator with a super gaussian mirror. The profiles are shown, from outside in, for conditions $R_0M^n > 1$, $R_0M^n = 1$, and $R_0M^n < 1$.

The modeling effort has proven to be useful in leading to optimum design choices for the laser-diode pumped Nd:YAG slab laser. However, models are informed and tested by experiments. The next section describes the progress toward the 100W minislab laser in the sequence of experiments through phase I of this program leading to the efforts under way in Phase II of this program.

1 Watt ring cavity single frequency Nd:YAG oscillator

During the first year of the research program the critical long lead items required for the high power miniature slab Nd:YAG laser were ordered. These items included the power supplies, the filter supplies to protect the laser diodes from voltage surges, the thermal electric coolers for controlling the laser diode temperature, and the fiber coupled laser-diodes themselves. The fiber coupled laser-diodes were a new product which were undergoing continued improvement. Therefore, we elected to order ten laser-diodes and work with the manufacturer to improve the performance and the reliability of the devices. The early devices were based on a 10W laser bar coupled to a 400μm fiber with a numerical aperture, NA = 0.4. These devices delivered up to 6W of power from the fiber.

One year after placing the order, the laser-diodes had yet to be delivered at the operating specifications. During that time the construction of the interface units to hold the laser diodes and the TE coolers was completed. The power supplies were delivered and accepted. The 1Watt active-mirror ring laser was designed in preparation for the delivery of the fiber coupled laser-diodes.

The motivation for the active-mirror ring laser was to test the laser diodes in actual use. This required that a monitor circuit be designed to protect against the temperature rise of the fiber coupling collet at the delivered 6W of average power. A second motivation for the active-mirror ring laser was to study the injection locking process, design and assemble all the electronic circuits required for injection locking. These electronic components will be used to injection lock the 50W minislab laser and eventually the 100W laser.

The 1 Watt active-mirror ring laser was tested in the summer of 1992. It used a bow-tie resonator shown in Figure 14. The resonator used an active mirror design in which the Nd:YAG gain medium was pumped by the re-imaged 5W output from the fiber coupled laser-diode. The resonator incorporated a Faraday glass rotator which consisted of a Brewster angle plate of Faraday glass in close proximity to a permanent magnet. With the rotator incorporated into the resonator the laser operated in a single direction which eliminated spatial hole burning and thus it operated in a single frequency. This oscillator was injection locked with a 300mW NPRO laser. The maximum locking ratio was measured to be 65:1. This laser had a 2.5% cavity loss, operated at a 27% slope efficiency and had a threshold pump power of 1.1W without the Faraday rotator and etalon, and a pump threshold of 1.7W with these elements in the resonator.

1 watt Active-Mirror Ring Laser

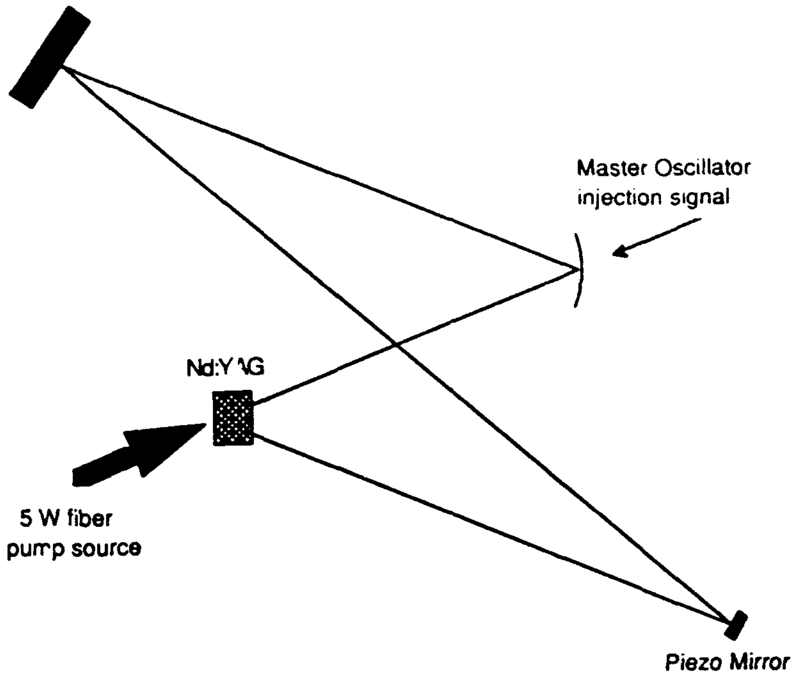

Figure 14. A schematic of the 1 Watt active-mirror ring Nd:YAG laser pumped by a single fiber coupled laser-diode. This laser operated at 27% slope efficiency, 1.1W pump power threshold, and a cavity loss of 2.5%. The laser was injection locked with a 300mW NPRO master oscillator.

5 Watt miniature slab Nd:YAG laser

Upon the completion of the testing for the 1W active-mirror ring cavity laser, design began for a 5 Watt miniature slab Nd:YAG laser. The motivation for this work was to test the laser slab mounting approach that would be used for the 50W laser that was to follow. In this design, the laser is pumped and cooled through the optical faces that also support the total internal reflection zigzag bounces of the laser resonator mode. Thus it is essential that a mounting scheme be devised that keeps the interface loss to a minimum but allows efficient pumping.

Figure 15 shows a schematic of the laser head design for the 5 Watt cw miniature slab Nd:YAG laser. Figure 16 shows a photograph of the 1.5mm x 6mm x 26mm Nd:YAG slab to help put the device into perspective. Figure 17 shows a photograph of the assembled laser head and the optical fibers that deliver the laser-diode pump power.

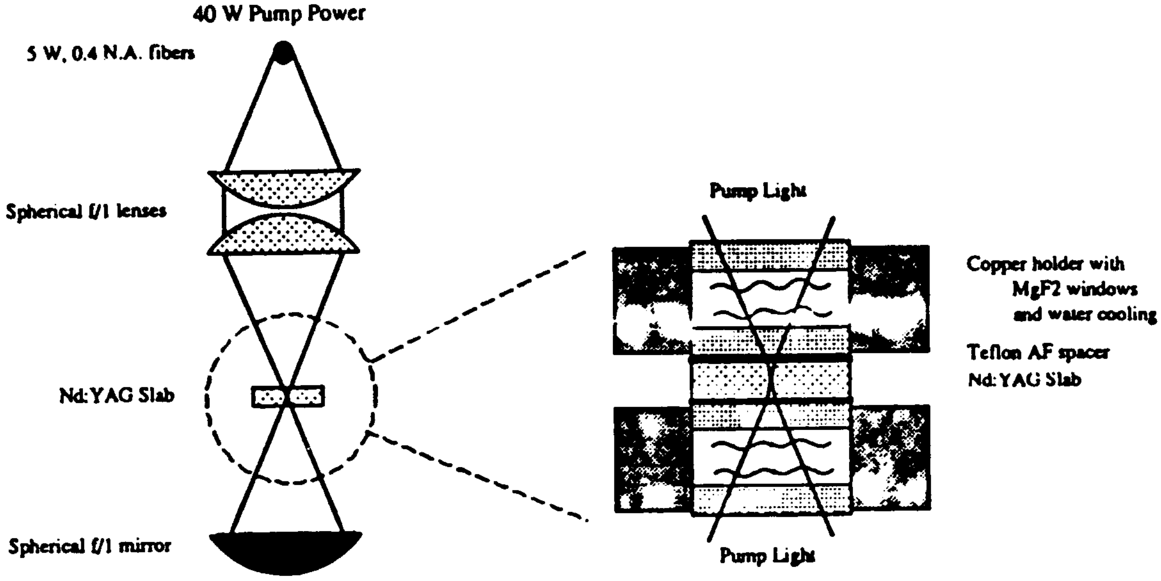

Figure 15. Schematic of the 5 Watt laser head design.

The individual fibers are held by stainless steel tubing soldered into a water cooled copper block. The output of the 5 fibers is re-imaged by the spherical lens into a line in the Nd:YAG slab. Laser diode pump power that is not absorbed by the 1.5mm thick slab is reflected back into the slab by the spherical mirror. The slab is sandwiched between water cooled, transparent MgF_2 windows. MgF_2 was chosen because of its high thermal conductivity, similar to that of Nd:YAG and its low index of refraction. The interface between the MgF_2 windows and the Nd:YAG slab consists of a thin Teflon AF spacer. Teflon was selected for its high optical quality and low index of refraction of $n = 1.300$. This laser head design avoids water cooling of the Nd:YAG slab TIR face yet allows efficient pumping and effective cooling of the face of the Nd:YAG slab due to the high thermal conductivity of the MgF_2 windows. A key element in this design is the Teflon AF spacer layer. This layer is less costly and easier to apply that the alternative of a dielectric film of SiO_2.

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The 5 Watt cw minislab Nd:YAG laser operated at a slope efficiency of 19% with a threshold pump power of 3.4W. The low threshold pump power and the high slope efficiency for this side pumped thin slab are due to the low 1.5% optical loss of the cavity. This is a direct result of the quality of the Teflon AF coating applied to the Nd:YAG slab.

Figure 18 shows the measured output power of this slab laser vs the input laser-diode pump power. The data was taken for TEM_{00} mode operation with a 4% output coupler. The performance of this side pumped miniature slab laser is the best reported to date for cw operation. Although not a true slab laser because of the line image pumping into the TEM_{00} mode volume, this laser design demonstrates all of the characteristics sought for the next step to the 50W slab laser. Of particular interest is the discovery of the low loss Teflon AF coating, the use of the transparent but highly thermally conductive MgF_2 windows and the successful use of thin tubes to hold the optical fibers in location for ease of pumping. This laser head design is simple, can be taken apart and reassembled with ease, and is scalable to higher average power levels.

The 5 Watt laser oscillator will be described in a paper to be presented at the Advanced Solid State Laser Topical Meeting to be held in February, 1994 in Salt Lake City. The paper to be presented describes the performance and the design of the laser and also describes the performance of the laser when operated at 1.32μm. [32]

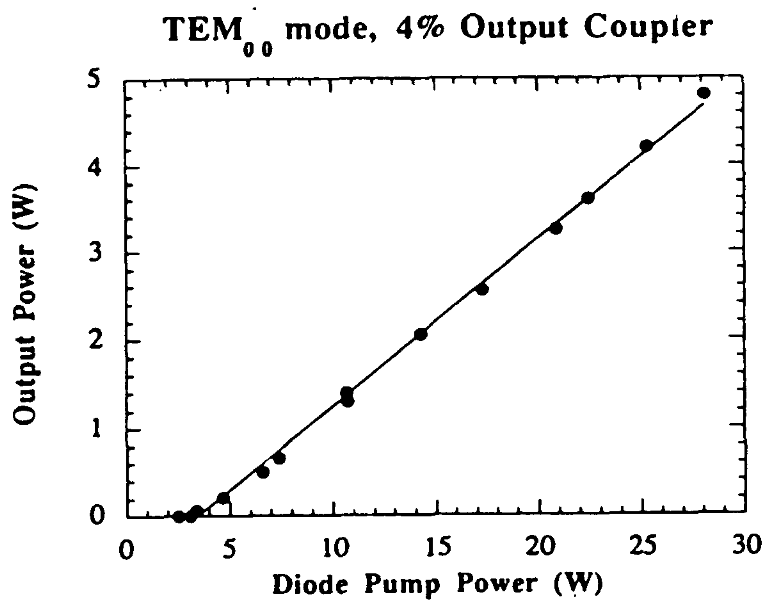

Figure 18. TEM_{00} mode output power vs input laser-diode pumping power for the 5 Watt laser.

50 Watt cw, TEM_{00} mode, miniature slab Nd:YAG laser

During the phase I of this program considerable efforts were placed on defining the fiber coupled laser-diode sources, working with the manufacturer to assure the quality of the devices, and working to devise acceptance tests for the devices that met the manufacturers approval and our own requirements. The original order for the fiber coupled laser diode bars was more than one year late in delivery by the summer of 1992. The order was subsequently renegotiated and delivery of 25 fiber coupled 15 Watt bars was initiated in late 1992 and early 1993. All fiber coupled diode lasers met acceptance tests and the order was completed late in the Spring of 1993.

The fiber coupled laser-diodes that were delivered were mounted in a new package to insure performance and operational life. The new package led subsequently to an improved mounting and temperature control approach in our laboratories. The mountings for the 25 laser diodes is now complete and the devices are ready to be installed. During this same time frame, the power supplies were up-graded to allow full computer control and monitoring. The diode lasers can now be individually monitored and controlled by the operator. The electronic protection circuits built into the power supplies is designed to shut the diode current off if the current exceeds a preset value or if the voltage required to drive the diode exceeds a preset value.

The 25 fiber coupled laser-diode bars deliver 10W of optical power from each fiber. The available pump power is therefore 250W which is adequate to pump a 50W minislab Nd:YAG laser.

The 50 Watt cw, minislab Nd:YAG laser head design is a derivative of the successful 5 Watt laser design. The features of this laser include a Brewster angle slab of dimensions 1.7mm x 1.8mm x 58.8mm. This slab, when pumped at the full power level is operating at 50% of the stress fracture limit of the slab. For cw operation the margin of safety should be adequate. Commercial lamp pumped kilowatt Nd:YAG lasers are designed to operate above the stress fracture limit. The kilowatt of optical output power reduces the heat dissipated in the laser rod to below the stress fracture limit. Figure 19 shows a schematic of the laser head design for the 50 Watt minislab laser.

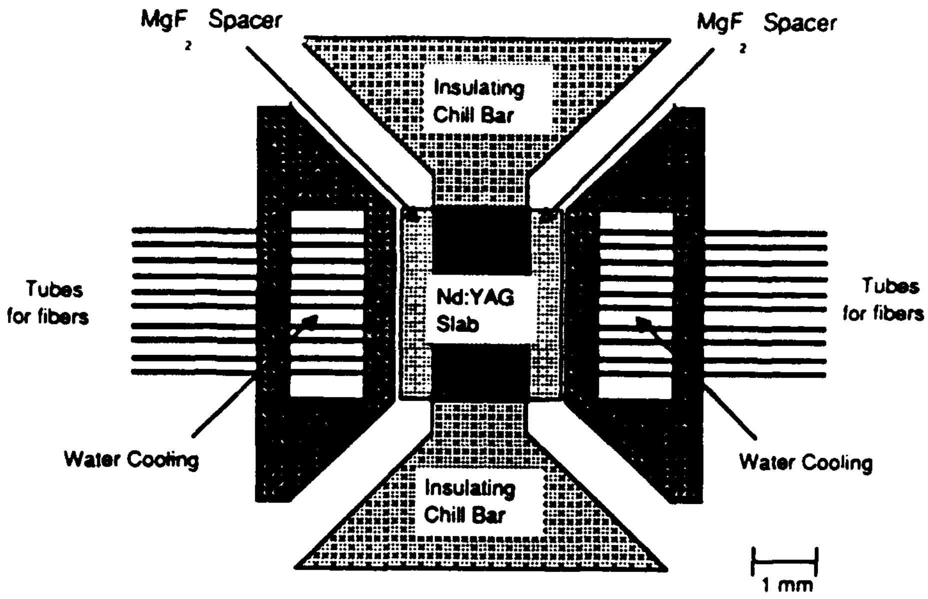

Figure 19. Schematic of the head design for the 50 Watt cw minislab Nd:YAG laser. The optical fibers are held in place by stainless steel hollow hypodermic needles that are soldered into the water cooled copper holder. The optical radiation from the fiber is transmitted through the MgF_2 window, through the thin Teflon AF layer and into the Nd:YAG slab. The face of the copper mount is gold coated to reflect the diode laser radiation that is not absorbed by the 1.5mm thick Nd:YAG slab on the first transit.

The features of this laser design include a thin 1.5mm slab for optimum thermal control. For this thickness of Nd:YAG approximately 70% of the diode pump radiation is absorbed in a double pass through the slab. The 3mm wide slab is uniformly pumped and uniformly cooled making this a true slab geometry. The calculated gain is 1.24 for 250 W of pump power. The Brewster angle slab ends are exposed for easy cleaning without the necessity of demounting the slab.

The MgF_2 window is 0.5mm thick and is water cooled directly. The MgF_2 window is in contact with the Teflon AF layer that is spun onto the Nd:YAG slab. The low index of refraction of the Teflon AF layer preserves the total internal reflection of the Nd:YAG slab while allowing the mounting stress between the MgF_2 and the Nd:YAG to be accommodated. The laser-diode pumping fibers are mounted on both sides of the slab in the orange grove arrangement to uniformly pump the slab. The copper mount assembly is soldered together to avoid leaks. The copper mount assembly has a large water flow

channel to minimize the pressure drop across the slab length. The slab is held by insulating bars on the top and bottom to control the thermal profile.

The laser head assembly is now under construction. The Nd:YAG slabs are being polished and are scheduled for delivery in early January, 1994. The optics has been ordered for the resonator which will be a single sided unstable resonator with magnification of M = 1.4 with an output coupling of T = 29%. Figure 20 shows the calculated output power vs the laser-diode pump power for this 50 Watt laser. The raw output from the one sided unstable resonator is predicted to be 70 W. If this beam is spatially filtered to achieve a TEM_{00} mode, the output is expected to decrease to 55W. This laser is clearly in the transition region where the slab dimensions are too wide to be effectively coupled by a TEM_{00} mode and the gain is too low to accommodate a full fledged super gaussian unstable resonator. The latter resonator will have to await the gain and size of the 100 Watt and higher average power laser-diode pumped, cw Nd:YAG lasers.

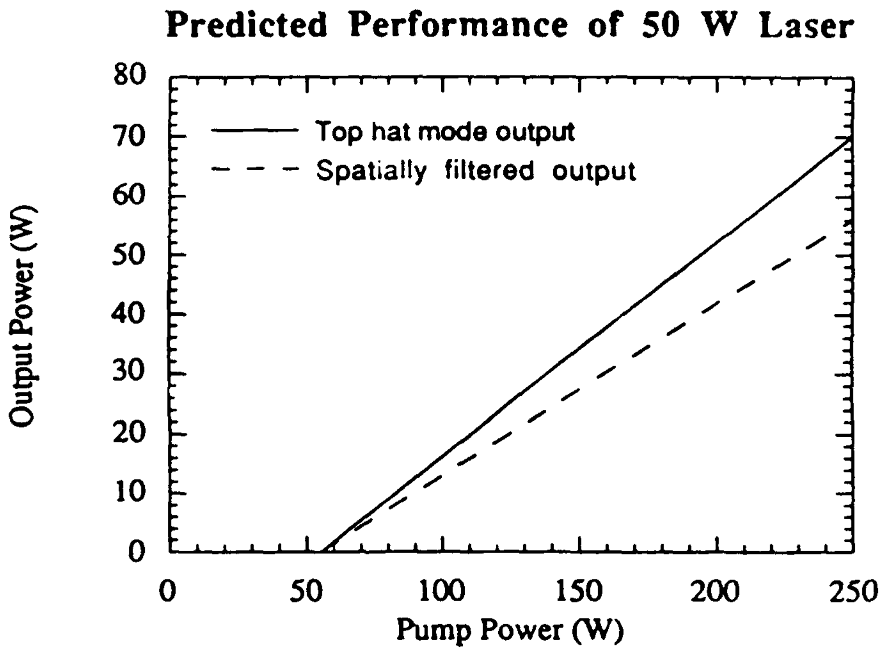

Figure 20. The predicted performance of the 50 Watt cw, minislab Nd:YAG laser. The top hat unstable resonator output is shown as a solid line. The spatially filtered gaussian TEM_{00} mode output is shown as the dashed line. The cavity loss is assumed to be 3.0%, the output coupling is T = 20%.

Projected performance of a 100W cw slab Nd:YAG laser

The projected performance of a 100W cw slab Nd:YAG laser can be scaled directly from the performance of the 50 Watt laser. The average power of a slab laser at fixed thermal load requires that the slab area be increased in proportion to the pumping power. Thus the 100 Watt laser slab can be 1.5mm thick by 6mm wide by 40mm long and operate at the same gain as the 50 Watt laser. However, the area can also be increased by increasing the length of the slab, or by adding a second slab to the optical resonator. We have considered the latter approach because it requires the minimum in new parts and because it allows polarization compensation to be introduced into the slab laser design if a quartz rotator is placed between the pair of identical slabs and if the slabs are designed with normal or near normal incident angle faces in place of the Brewster angle faces now used.

Figure 21 shows the predicted performance of a 100 Watt laser assuming that the design is a scaled version of the 50 Watt laser that is currently being completed. This laser utilizes a zigzag slab with uniform pumping and uniform cooling. It utilizes an unstable resonator for efficient power extraction from the gain medium. A spatial filter is used to convert the unstable resonator top hat beam into the TEM_{00} mode that is desired.

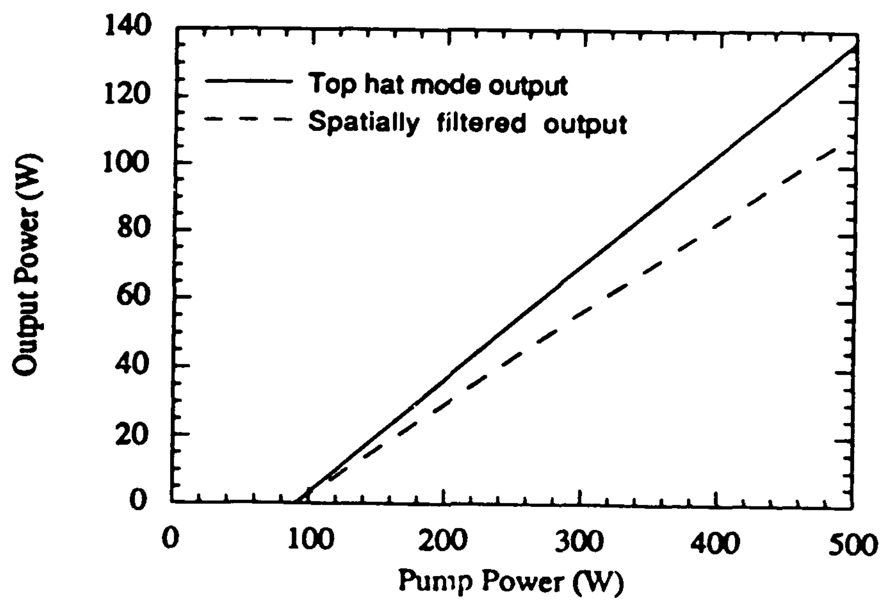

Figure 21. The predicted performance of a 100 Watt cw, minislab Nd:YAG laser. The slab dimension are scaled with the power to keep the same thermal loading as the 50 Watt laser. The solid line is the top hat output from an unstable resonator. The dashed line is the spatially filtered output to yield a TEM_{00} mode.

The 100 Watt laser does require 500 watts of pump power. At this time the additional 250 watts of pump power can be met by purchasing an additional 25 fiber coupled 15 watt diode bars of the type currently in hand. However, the power supplies were designed with adequate margin to pump 20 watt bars that could provide 15 watts from the fiber. A fiber coupled diode-laser product that meets this performance specification is now being advertised at a price of $5350. However, this product has yet to be delivered and tested. If available, the cost of the 250 watts of power at the advertised price is $91,000. The long term strategy of fiber coupled laser-diodes for pumping slab lasers is beginning to pay dividends. That is, improved diode capability can be easily accommodated by the current power supplies and by the slab design without forcing the redesign of the laser head. Further, as the fiber coupled laser-diode power brightness continues to increase with improvements in coupling efficiency and the use of a smaller core fiber with lower numerical aperture, the gain of the Nd:YAG slab can be increased at a fixed power level thus enabling the use of more sophisticated unstable resonator designs for efficient power extraction from the Nd:YAG laser.

B. Nonlinear Frequency Conversion

When this program was initiated one goal was to explore efficient nonlinear frequency conversion. For continuous wave laser sources, efficient frequency conversion requires that the electric field be enhanced. Enhancement of the field can be accomplished by placing the nonlinear crystal inside of the laser cavity as was first demonstrated for a diode pump laser by T. Y. Fan *et al.* [33] who doubled a Nd:YLF laser using $MgO:LiNbO_3$ to generate approximately 1mW of green output. Internal SHG has been pursued by other groups to generate watt level green output power levels. However, internal SHG couples the problems of simultaneously optimizing the laser cavity and the nonlinear optical interaction and often compromises both.

We elected early in our frequency conversion studies to pursue resonant SHG in an external cavity. This approach was first studied in 1966 by Ashkin *et al.* [34] who achieved less than one percent conversion efficiency. In early work using monolithic $MgO:LiNbO_3$ external frequency doublers, Kozlovsky *et al.* [35] were able to demonstrate 56% conversion efficiency to the second harmonic. That is, they doubled a 53mW cw Nd:YAG NPRO and generated 30mW of green in a 12mm long $MgO:LiNbO_3$ crystal.

The external resonant SHG approach separated the optimization of the laser source from the optimization of the frequency doubling process. It, however, demands that the laser operate in a single transverse and single axial mode so that the laser output be efficiently mode matched and frequency locked on resonance to the external enhancement cavity. This laser requirement was met by injection locking as discussed above. These developments, coupled with improved nonlinear materials, led us to propose to study high power nonlinear frequency conversion.

Second Harmonic Generation of Nd:YAG in PPLN and in LBO

The successful injection locking of the 13W lamp pumped, cw, Nd:YAG laser by Nabors *et al.* [25] provided the first opportunity to explore external resonant cavity SHG at higher power levels. We successfully conducted resonant doubling in an LBO crystal grown at Stanford by the Feigelson group. In the first experiment, during the first year of this program, we reported converting 13W of 1064nm to 3.5W of 532nm.

That work was quickly followed by frequency doubling of an 18W cw, injection locked, lamp pumped Nd:YAG laser to generate 6.5W of single mode 532nm output by Yang *et al.* [36]. The experiment generated single frequency green output at 45% conversion efficiency. Further, the LBO proved to be robust to the optical field but was sensitive to crystal temperature changes which led to the optical coating separating from the crystal surface. Nevertheless, this experiment remained in operation for more than one year and provided 532nm radiation for pumping optical parametric oscillators and for preliminary investigation of 266nm generation by external cavity resonant SHG in BBO. The BBO experiment led to 30mW of output at 266nm but was hampered by poor optical coatings on the cavity mirrors.

Using the external resonant cavity that was constructed for the LBO SHG experiment, Dieter Jundt explored SHG in lithium rich $LiNbO_3$ [37] and in periodically poled lithium niobate (PPLN) [38]. He was successful in demonstrating 69% conversion efficiency in lithium rich lithium niobate. This experiment also showed for the first time that at higher average power levels thermal instabilities would limit the nonlinear frequency conversion.

Using a periodically poled crystal grown on the Laser Heated Pedestal Growth station, invented by Fejer in 1981, D. Jundt demonstrated the first high conversion efficiency, high power nonlinear frequency conversion in a quasiphasematched material [38]. In this

experiment Jundt converted 4.6W of cw 1064nm to 1.7W of green. What was remarkable was the crystal size of only 250 μm in diameter and 1.24 mm in length. The quasiphasematched interaction in lithium niobate allows the use of the d_{33} coefficient which is an order of magnitude larger than the usual d_{31} coefficient. Further, the quasiphasematched interaction is not susceptible to photorefractive damage thus allowing the power levels at the focus of the beam to exceed 10MW/cm^2 of continuous intensity. Figure 22 shows the second harmonic power vs. fundamental power and the conversion efficiency for SHG in a periodically poled lithium niobate crystal 1.24 mm in length.

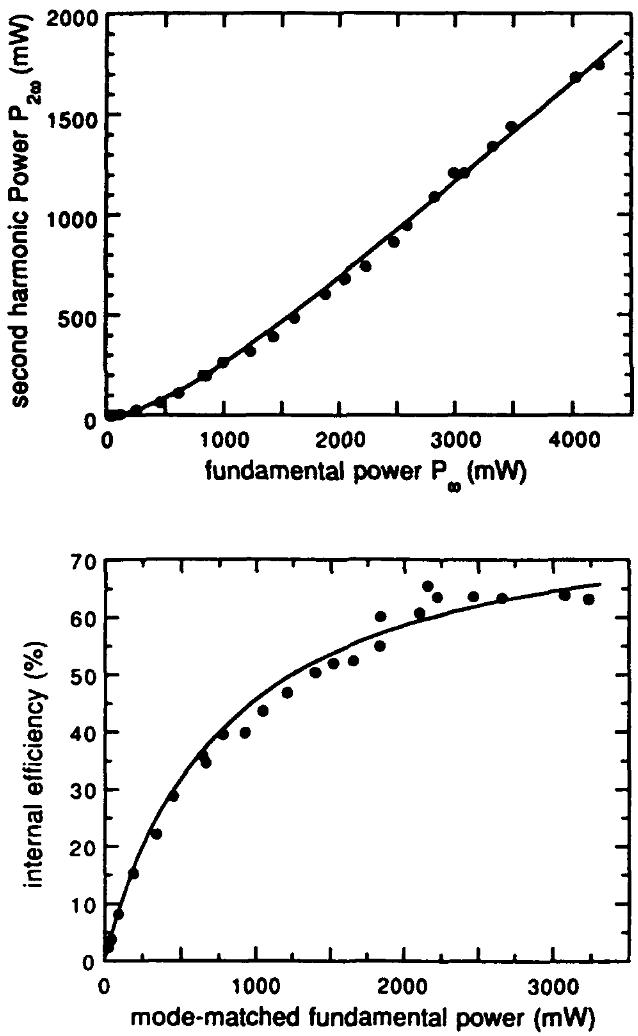

Figure 22 (a) Second harmonic power measured outside of the external enhancement cavity vs fundamental power incident on the cavity for a PPLN crystal of 1.24mm length. The domain spacing is 3.47μm for this sample. (b) Internal conversion efficiency for the periodically poled 1.24 mm sample.

This quasiphasematched interaction in a bulk crystal represents a significant breakthrough in nonlinear optics. For the first time, the phasematching is under the direct control of the experimentalist. To illustrate this, Jundt grew PPLN crystals with a domain length of 6.3μm and doubled the 1.32μm line of Nd:YAG to generate red; with a domain length of 3.5μm and doubled 1.064μm to generate green; and with a domain length of 2.1μm and doubled 0.93μm to generate blue. A color photograph of these experiments illustrates clearly the power of quasiphasematching. Jundt also showed that very small diameter and very short crystals of PPLN could handle high average powers and intensities. The $10 MW/cm^2$ intensity at 1064nm incident on the PPLN crystal shows that lithium niobate can handle kilowatts of average power in mm crystal sizes.

The success of this first device demonstration of PPLN has motivated our continued efforts to prepare, by electric field repoling, quasiphasematched lithium niobate. We believe that periodic poled lithium niobate will offer significant improvements in device design and performance for SHG and for OPO operation.

A careful consideration of external cavity resonant SHG shows that the conversion efficiency is dominated by optical losses the resonator and the nonlinear crystal. For example, the conversion efficiency is limited to 60% for a round trip loss of 1%. The conversion efficiency improves to greater than 80% for a round trip loss of 0.5%. Finally, the conversion efficiency increases to 94% for a round trip loss of 0.2%. As these losses are reduced, the optimum crystal length reduces from 1cm to less than 2mm. This in turn allows the crystal to withstand higher average power loadings without breaking the phasematching condition.

Here we cite examples of the trend to lower loss and to shorter crystals for efficient external cavity resonant SHG. In a follow-on experiment to the original monolithic external cavity $MgO:LiNbO_3$ experiment of Kozlovsky *et al.* [35], A. Arie constructed and demonstrated a monolithic doubler of only 8mm length in $MgO:LiNbO_3$. This doubler converted 200mW of NPRO power to 115mW of green at a conversion efficiency of 62%. Shortly after, Gerstenberger *et al.* [39] converted 310mW of NPRO power to 200mW of green at 65% conversion efficiency in a 5mm length of $LiNbO_3$. This demonstration led to a commercial product introduced by Lightwave Electronics Corporation based the diode laser pumped Nd:YAG NPRO frequency doubled to 532nm by external resonant SHG in a monolithic $MgO:LiNbO_3$ resonator. Finally, the highest conversion efficiency reported to

date is 85% for external cavity resonant doubling in KTP of a 700mW cw Nd:YAlO$_3$ laser by Ou *et al.* [40]. In summary, in a span of five years, the cw doubling efficiency has increased from less than 1% to greater than 80% and the average output power at the second harmonic has increased from 30mW to greater than 11W. We can expect that the progress toward higher average power levels will continue, limited only by the availability of diffraction limited, single frequency, cw Nd:YAG laser sources.

Nd:YAG pumped cw 2μm OPO in Lithium Niobate

The monolithic lithium niobate frequency doubler has proven to be stable, efficient and reliable in both research experiments and in commercial products. The concept was extended to optical parametric oscillators (OPO) first by Schiller *et al.* [41] who demonstrated a quadruply resonant OPO based on 1.064μm pumped resonant SHG in lithium niobate, followed in the same crystal by the generated green pumping a nearly degenerate cw OPO. The input field, the generated second harmonic field, and the signal and the idler field were each resonant within the total internal reflection (TIR) lithium niobate nonlinear crystal. The threshold for this quadruply resonant OPO was less than 1mW at the 1.064μm input. The device operated stably in a single axial mode at the signal and idler waves.

The monolithic TIR OPO concept was extended by Serkland [42] to a cw, 1.064μm pumped, 2.12μm output OPO. The device used birefringence to input couple the pump wave and used TIR to contain the signal and idler fields. Frustrated prism coupling was used to outcouple the resonant signal and idler fields. This OPO used lithium niobate in an off-angle phasematching mode. Thus Poynting vector walkoff was present which increased the threshold of the device by a factor of 20 over noncritically phasematched OPOs. Further, the threshold was increased compared to a 532nm pumped OPO by a factor of wavelength cubed, or a factor of 8. Given this much higher expected threshold, the TIR OPO required very low resonator losses at the resonated 2μm fields to reach threshold at the available 300mW of pump power.

The advantages of the monolithic TIR design are intrinsic stability, very low loss TIR resonators, and no optical coatings which reduces the cost of the devices. Figure 23 shows a schematic of the lithium niobate OPO and the optical paths for the pump and signal and idler waves. Prior to the attempt to operate the device as an OPO, SHG experiments were conducted using a Tm:YAG 2.0μm laser source. These doubling experiments

demonstrated that the lithium niobate TIR resonator had a measured finesse of greater than 6000 at the 2μm wavelength. Thus the measured round trip power loss at 2μm in lithium niobate is less than 0.1%. This low loss means not only a reasonable threshold, but that lithium niobate will stand very high average power levels at the 2μm wavelength.

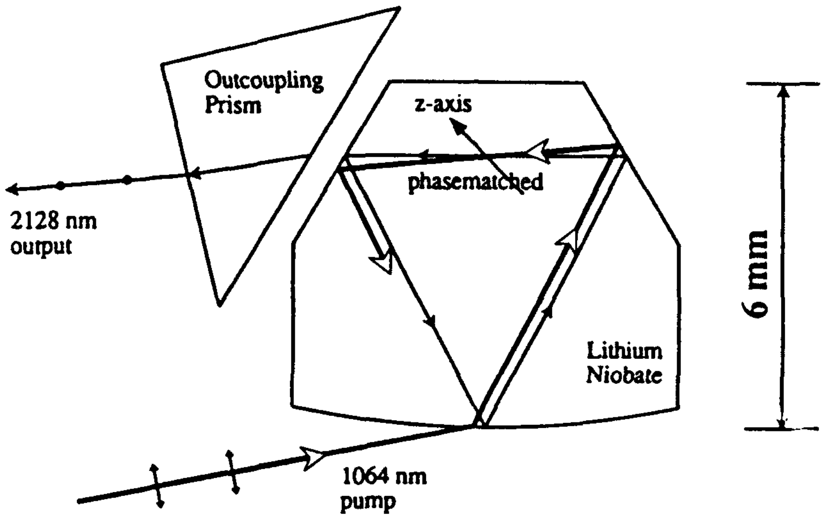

Figure 23. Schematic of the monolithic lithium niobate TIR OPO pumped at 1064nm. The measured cw threshold was 130mW. This is the first cw OPO operating with an infrared pump wavelength.

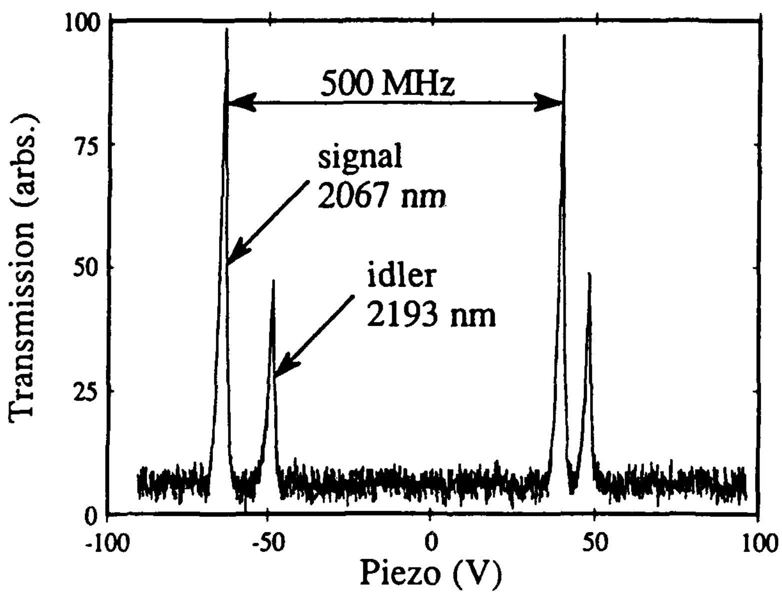

Figure 24. The output spectrum of the cw, TIR lithium niobate OPO near 2.1μm. The OPO operated in a single axial mode with a high degree of stability. This OPO may form the coherent master oscillator for amplifiers in the 2.1μm region. The output at 2.19μm is coincident with a 2-photon absorption line of Xe which may be useful as an optical clock.

532nm pumped cw Singly Resonant OPO in KTP

For 25 years its has been understood that the singly resonant optical parametric oscillator (SRO) offered significant advantages compared to the doubly resonant optical parametric oscillator (DRO). These advantages include: continuous tuning without the presence of the 'cluster effect' of the DRO which involves the simultaneous resonance of both the signal and the idler waves for operation; wide tuning range since only one wave needs to be resonated; potential for high conversion efficiency since the non resonant wave of the SRO is directly coupled from the device; and single frequency operation since the device is homogeneously saturated and thus the first cavity mode to reach threshold will dominate. These advantages came a the price of higher threshold. The DRO threshold is proportional to the product of the losses, $\alpha_i\alpha_s$,while the SRO threshold is proportional to $2\alpha_s$. Thus for 1% loss, the SRO threshold is 200 times that of the DRO threshold.

A few years ago, Alan Nilsson, who completed a thesis on the properties of the NPRO Nd:YAG oscillator, wrote that a nearly impossible Ph.D. thesis would be to undertake to demonstrate the first cw SRO. Fortunately, Steven Yang did not read Alan's thesis until he had undertaken to build the first cw SRO.

In a series of elegant experiments, Steven Yang explored the SRO operation, theoretically and experimentally, which culminated in the first successful operation of a cw SRO pumped by a cw, frequency doubled, injection locked Nd:YAG source. The SRO used KTP as the nonlinear element. The approach to the successful SRO operation involved using Nd:YAG in a spiked mode of operation with between 25 and 75W of peak power at microsecond pulse lengths to explore the SRO threshold. The SRO was then operated with pump wave feedback and with idler wave double passing through the nonlinear crystal to reduce the threshold by a factor of four to the 2.8 Watt level. This experiment was published in June, 1993 [43]. This first SRO generated more than 1 Watt of output power at the 1.03μm wavelength and operated in a single axial mode. Yang then investigated the characteristics of the DRO to SRO transition in detail [44]. He found that the SRO can withstand some feedback at the nonresonant wave if it is operated well above threshold. This in turn, led to experiments to test the theoretical prediction by operating a ring cavity SRO. However, to accomplish this task, the available 6.5 Watts of 532nm radiation from the frequency doubled Nd:YAG laser had to be increased.

Increasing the 532nm power required a re-engineering the injection locked, cw, lamp pumped Nd:YAG laser source. Yang increased the laser power by adding a second laser rod in series with the first with a quartz rotator between the rods to cancel the thermally induced birefringence. This ring cavity laser was then injection locked with a 300mW NPRO. The laser generated 24 Watts of TEM_{00} mode, single frequency, cw, output at 1064nm. The output of the laser was then mode matched into an external cavity resonator into which was placed an 8mm thick LBO crystal. The schematic of this experiment is shown in Figure 25.

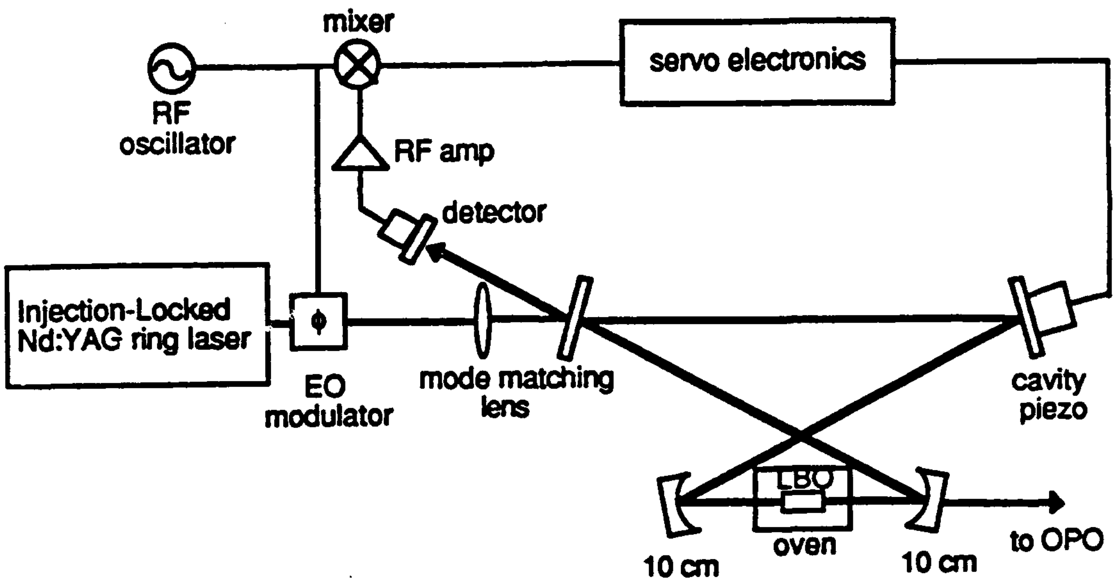

Figure 25. External resonant second harmonic generation schematic.

The external cavity resonant SHG output power vs input fundamental power is shown in Figure 26. The conversion efficiency is also plotted. The lower loss of the LBO crystal coupled with the higher pump power led to a conversion efficiency of 60%. The output power reached 11.2 Watts of 532nm for 19 Watts of incident 1064nm power.

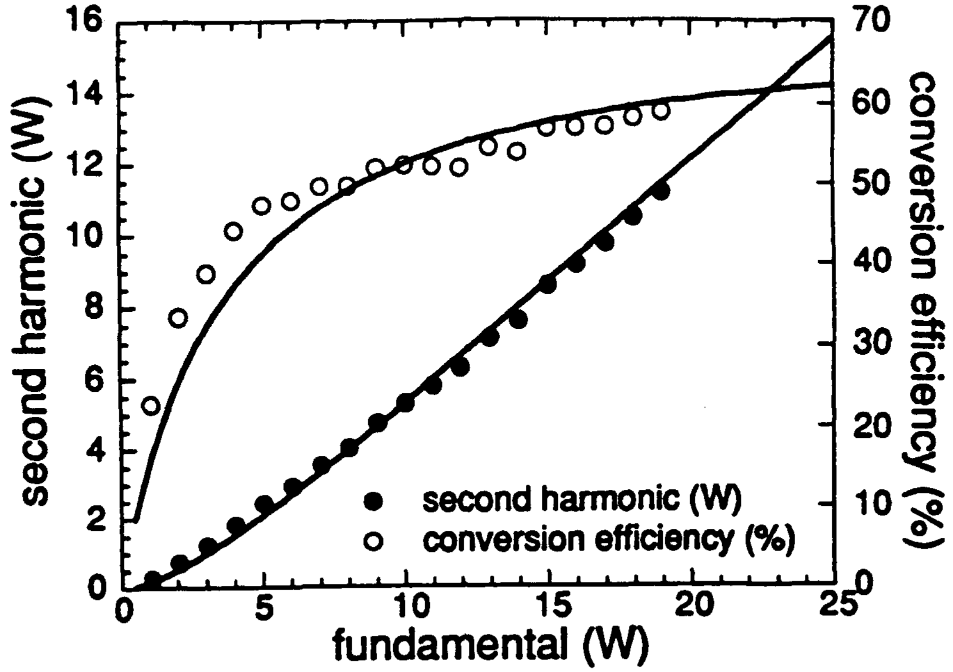

Figure 26. Generated second harmonic output power and conversion efficiency vs input fundamental power. The LBO doubling crystal is 8mm long. The maximum output power at 532nm is 11.2 Watts.

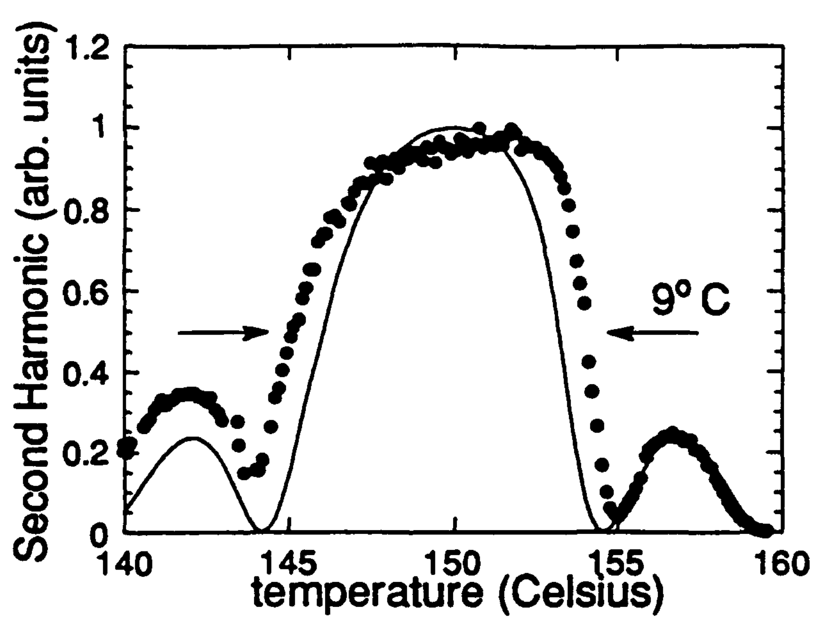

Figure 27. Measured (dots) and calculated (solid line) phase matching curve for LBO under high power SHG generation. The peak of the phase matching curve has been normalized to 11.2 Watts of green. The crystal is clearly in saturation which means that it is too long for this interaction. (after S. Yang ref 46)

The 11.2 Watt 532nm source was first operated in late June, 1993. It has operated since that time without incident. The 11.2 Watts of single mode green radiation allowed the pumping of a cw, ring cavity, SRO to well above threshold. To date, this remains the highest power cw 532nm single axial mode laser operating in the world. The linewidth at 532nm is less than 10kHz.

With the improved 532nm source, Yang initiated a study of a ring resonator SRO in which the pump makes one pass through the nonlinear crystal and there is some feedback at the nonresonant idler wave due to residual reflectance at the mirror coatings. The experiments confirmed the theoretical predictions that when operated well above threshold, the SRO tuned continuously and operated as an SRO without modulation due to the small amount of feedback at the nonresonant wave. This experiment was important because it led to a greatly simplified cavity design for the SRO.

Figure 28 shows a schematic of the ring cavity KTP SRO. The mirrors were coated to be high reflectance at the resonated signal wave but were high transmittance at the nonresonated idler wave.

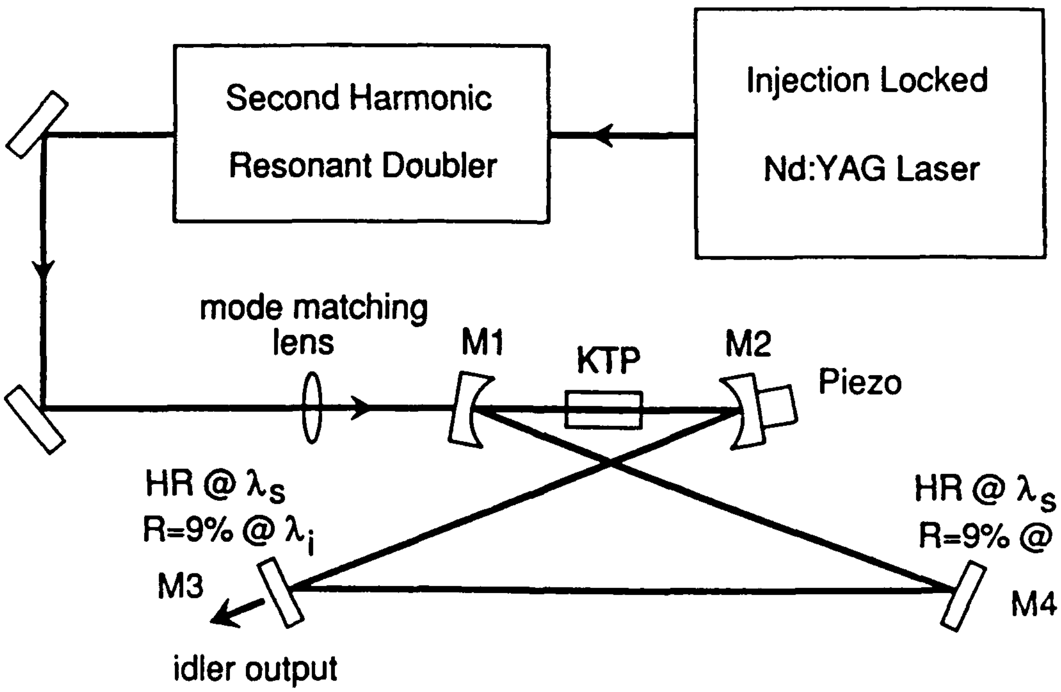

Figure 28. Schematic of the ring cavity KTP Singly Resonant Optical Parametric Oscillator.

Figure 29 shows the SRO output power vs the input 532nm pump power. The measured threshold is 4.3W. The maximum output power is 1.9 Watts in a single axial mode for 6.8 Watts of 532nm pump power. The slope efficiency of the OPO is greater than 78%. At higher pump power levels the OPO operated in more than one axial mode. Operation in higher order modes are probably due to complete pump depletion on axis with residual gain off axis allowing higher order spatial modes to oscillate.

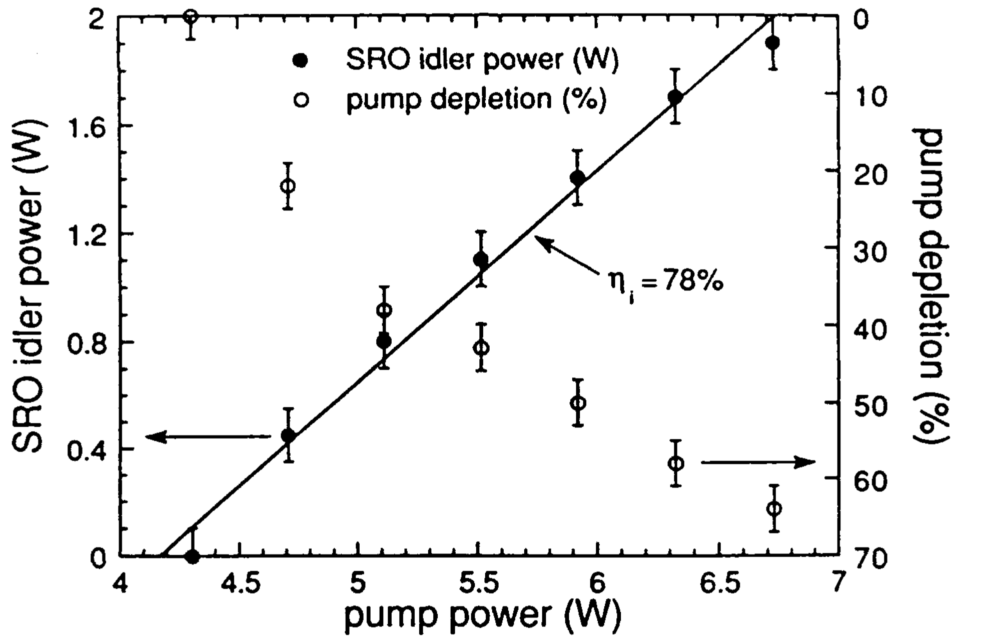

Figure 29. The SRO idler output power vs the input 532nm pump power. The maximum output power in a single axial mode is 1.9 Watts for 6.8 Watts of pump power.

Based on these experiments, the cw SRO offers the potential for very high average power tunable output at a high conversion efficiency.

Figure 30 shows the output spectrum of the SRO illustrating the single frequency nature of the output. This SRO is continuously tunable. Its output frequency spectrum has a linewidth of less than 1MHz and is probably on the order of the 10kHz linewidth of the pump laser source. The SRO operated in a single axial mode without any linewidth control elements in the cavity. The SRO conversion efficiency and single mode spectrum compare very favorably to a titanium sapphire laser, for example. Under similar pumping conditions, the titanium sapphire laser operates in a multiple axial mode spectrum and when line narrowed operates at less than 1 Watt of output power.

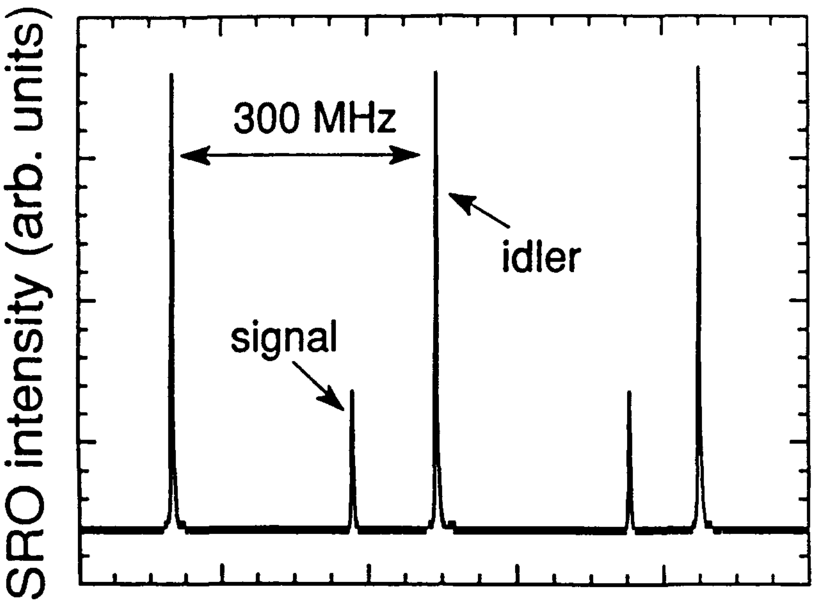

Figure 30. The axial mode spectrum of the SRO showing single frequency operation.

In summary, we have extended nonlinear frequency conversion to high average power levels by external cavity resonant second harmonic generation and by cw singly resonant optical parametric oscillation. We have laid the ground work for efficient nonlinear conversion of cw laser sources at tens of watts of average power. Further, we have demonstrated tunable parametric oscillation in the 2 μm region for the first time with cw pumping.

We can expect that second harmonic generators and optical parametric oscillators will continue to make progress in both power and efficiency as the laser sources increase in power. Progress in both the laser sources and in the optical properties of nonlinear crystals has led to the recent advances. This progress is reflected in the re-introduction of OPOs as commercial products and their rapid acceptance as the preferred sources of tunable radiation.

C. Future Directions and Summary

50 Watt cw TEM_{00} mode minislab Nd:YAG laser

The design for a TEM_{00} mode laser-diode pumped, 50 Watt cw, minislab Nd:YAG laser is complete, and all of the components required for the experiment have been received or are in the final stages of being completed. This laser source will utilize advances in design such as a unique Teflon AF coating on the Nd:YAG slab surface; the use of a MgF_2 window for transmitting the laser diode pump light but also for directly cooling the Nd:YAG slab surface; and the use of fiber coupling for uniformly pumping the Nd:YAG slab with 250W of diode power.

We expect the laser to generate first light in late January, 1994. We will explore the laser operating parameters of power output vs input pumping power, slope efficiency and threshold pump power, transverse mode control, and spectral control by the use of injection locking. This laser will then become the pump source for high average power nonlinear frequency conversion studies.

100W cw minislab Nd:YAG laser

Based on the measured performance of the 50 Watt minislab Nd:YAG laser, we will initiate the design and construction of the 100 Watt cw minislab Nd:YAG laser. At this time we are weighing the options of TEM_{00} mode operation vs unstable resonator operation and the options of one slab vs two slabs in series with the possibility of birefringence cancellation. The additional 25 fiber coupled laser-diodes needed to pump the 100 Watt laser will be ordered early in 1994.

The 100 Watt minislab Nd:YAG laser is the first diode-laser-pumped laser that takes us across the low gain barrier and into the high gain region where unstable resonators can operate efficiently. This laser will demonstrate all of the operating features that will allow power scaling to the kilowatt cw power output range and beyond. The 100 Watt cw minislab Nd:YAG laser will also take us into a new region operation where the slab geometry has a clear advantage over side pumped rod geometry. It will be the highest power, cw, single mode, single frequency laser in operation. Further, its design will incorporate the advantages of ease of assembly and repair, small size, ease of upgrade via the fiber coupled laser-diodes, and the potential for repair during continuous operation.

High average power nonlinear frequency conversion

The successful operation of the 50 Watt cw minislab Nd:YAG laser in 1994 and the 100 Watt cw minislab laser to follow will offer an unprecedented opportunity to explore high average power, cw, nonlinear optical frequency conversion. We plan to study efficient SHG be external cavity resonant second harmonic generation. For this study we will explore LBO and BBO since BBO offers significantly wider temperature acceptance bandwidth. The angle phasematched BBO requires the 50 Watt and above pump power to enter into an efficient conversion regime.

The development of periodically poled lithium niobate, PPLN, for nonlinear optical devices continues along two separate fronts. We are exploring electric-field repoling of lithium niobate at room temperature using pulsed electric fields applied to wafer samples 1/2 mm thick. This work has been making progress as we hope to demonstrate gratings for quasiphasematched interactions early in 1994. At $10 MW/cm^2$ intensity levels, a 1/2 mm thick, 5 mm long sample of PPLN will support more than 1kW of average power without optical damage. Further, the acceptance angle and the acceptance temperature are significantly improved relative to standard lithium niobate. In addition, there is work underway to grow PPLN from the melt. This research offers the potential for obtaining large area samples which can be useful for frequency conversion of Q-switched, high peak power, laser radiation.

We have placed emphasis on PPLN because it offers the potential to engineer the phasematching characteristics to the device of interest. For example, a PPLN OPO pumped directly by 1064nm offers the potential to generate tunable output in the 1.4 to 4.3μm spectral region.

The work to date has been presented at a special summer school on Quantum Electronics by Robert L. Byer and is to be published in the proceedings [47].

In summary, during the first phase of this research program we have frequency stabilized Nd:YAG lasers to unprecedented levels of stability, both relative and absolute. We have investigated single mode operation of high power cw Nd:YAG lasers by injection locking. We have designed and characterized fiber coupled, laser-diode pumped minislab Nd:YAG lasers at the 1W, 5W and in the near future 50W power levels. We plan to extend the work to the 100W power level. We have efficiently frequency doubled Nd:YAG with up to 11.2W of output power in the green. We have operated the first cw 2.1μm infrared OPO. Finally, we have demonstrated the first cw, singly resonant OPO in KTP with 1.9W of single mode output power.

III. Scientific Personnel Supported by this Contract

Principal Investigators

Professor Robert L. Byer	Applied Physics Department

Other Scientific Faculty and Staff

Martin M. Fejer	Assistant Professor	Applied Physics
Robert C. Eckardt	Sr. Research Assoc.	Ginzton Laboratory
Eric K. Gustafson	Research Associate	Ginzton Laboratorv
Tony Alfrey	Staff Scientist	Ginzton Laboratory

Students and Degrees Awarded

Robert C. Eckardt, Applied Physics, Ph.D. 1991
Deiter H. Jundt, Applied Physics, Ph.D., 1991
Eric Lim, Applied Physics, Ph.D., 1991
Ben Yoo, Electrical Engineering, Ph.D. 1991
Stephen Yang, Electrical Engineering, Ph.D., 1993

Robert Shine	Nick Sampas	Darwin Serkland	V. Sirutkaitis
Todd Merrill	Chris Rella	Michael Bortz	L. Eyres

IV. List of all Publications Supported by this Contract DAAL03-90-C-0026

1. Steven T. Yang, C. C. Pohalski, E. K. Gustafson and R. L. Byer, "3.5W cw 532nm radiation by resonant external cavity SHG of an 8.5 watt Nd:YAG laser in LBO," presented as an Invited Paper MF1 at Advanced Solid State Lasers Topical Meeting, Hilton Head, SC March 18 - 20, 1991

2. Dieter Hans Jundt, "Lithium niobate: single crystal fiber growth and quasi phase matching," Ph.D. dissertation, Applied Physics Department, Stanford University, (August 1991); Ginzton Laboratory Report No. 4855 (Stanford University, Stanford, CA, August 1991).

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10. Robert L. Byer, "Advances in Nonlinear Optical Materials and Devices," Proceedings of the Fifth Toyota Conference on Nonlinear Optical Materials, Aichi-ken, Japan, Published by North Holland, 1992

11. Ady Arie, Eric K. Gustafson and Robert L. Byer, "Heterodyne spectroscopy of Iodine using diode-laser pumped solid state laser," presented at the OSA Annual Meeting 1992

12. Ady Arie, E. K. Gustafson, and R. L. Byer, "Absolute frequency stabilization of diode-laser-pumped Nd:YAG lasers using the Doppler free absorption line of Iodine, presented at CLEO 1992

13. R. J. Shine *et al.*, "Design considerations for a 50-watt cw, fundamental mode, diode-pumped solid-state laser," SPIE 1865, pp. 17-27, (1993)

14. R. J. Shine Jr., A. F. Alfrey and R. L. Byer, "A 5-Watt 1.06μm and 1-Watt 1.32μm, cw, TEM_{00} mode, Diode-Laser-Pumped, Nd:YAG Slab Laser, " to be presented at the Advanced Solid State Laser Topical Meeting, February 1994, Salt Lake City, Utah

15. Darwin Serkland, "CW optical parametric oscillation near 2.1μm pumped by 1064nm," presented at the LEOS conference, San Jose, CA November 1993

16. S. T. Yang, R. C. Eckardt, and R. L. Byer, "Continuous-wave singly resonant optical parametric oscillator pumped by a single frequency resonantly doubled Nd:YAG laser, " Opt. Lett. 18, pp. 971-973, (1993)

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